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Proof-of-concept Demo for Collaborative Machine Room Planning in Virtual Reality

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The use of 2D drawing in the elevator machine room planning has been a critical challenge in high-rise construction project. In this thesis, the use of a multi-user VR application in complex machine room planning process is investigated via case studies. Four real-life high-rise elevator projects from KONE in USA, United Arab Emirates, Malaysia, and Indonesia are involved. The aim is to identify the benefits of multi-user VR from the user and business perspective and how this technology should be applied in the process. The study utilised design thinking model as the methodological framework. Interview and user testing with the emphasis on replicating real design review and construction planning tasks were conducted remotely to test the multi-user VR environment.

The results suggest that multi-user VR has great benefits in the process. From a user perspective, the technology serves as an intuitive tool for complex design communication and planning as well as facilitates the collaboration between teams. Users' confidence in the construction project is enhanced and critical design issues can be found easily in the early stage. From a business perspective, the use of multi-user VR saves cost and time by avoiding costly mistakes and increasing efficiency. Waste materials and the need for travelling decrease, which leads to a more sustainable collaboration within construction industry. Adopting the technology also enhances the company image. For early adoption, multi-user VR should be considered on a case-by-case basis with optimal use cases in design review and construction planning. Overall, the study presents the view from the industry on the role of VR in construction project and contributes in closing the knowledge gap between academia and the industry. The results suggest the need of a true cost-benefit of implementing VR in construction companies. Besides, future studies should focus on establishing the fluid communication between BIM authoring tool and VR to facilitate the adoption of VR in the construction industry.

Keywords Multi-user VR, Collaboration, Construction planning, Design review

Contents

Preface

First of all, I want to express my utmost gratitude towards Dr. Sanni Siltanen and Prof. Katja Hölttä-Otto for their constant supervision and support. Thank you both for always trusting and respecting my decision as well as giving me the freedom to shape the thesis as I was hoping it to be. Besides, I want to thank Sanni for teaching me invaluable professional and life knowledge as well as providing with endless possibilities to grow. You have made, and what I have learnt from you, will continue to leave a significant positive impact both on my career and personal life. Moreover, I am thankful of Katja for her patience to let me write this thesis in the most flexible way and giving me valuable advice throughout the process. Furthermore, I want to also thank Reetta Turtiainen for her guidance and comments that really helped me approach this thesis from a fresh perspective and make it as interesting as it could be.

I have been fortunate to be able to conduct this thesis project at KONE with amazing people. Thank you, Peter Eagling, for your guidance, assistance, and giving me many valuable advice on how I can progress in the industry. I am also grateful to have Paulina Becerril as my colleague and friend throughout the project. Thank Paulina for your constant support and kindness to help me out whenever I needed. I also truly appreciate the help of Amelia Veronica, Daniel Maughan, all participants and KONE Training Centers in making our remote user tests as successful as they were. Besides, I would like to thank Iiro Naamanka and Antti Poikonen from 3D Talo for being so supportive and your quick response to address my feedback in the development of the VR environment.

Most of all, I am beyond grateful to my girlfriend – Lia for moving along with me throughout this journey. Thank you for always staying by my side, taking care of me and believing in me. You have given strength to go through all the ups and downs in life so that I could firmly move forward and come across all the hardship. Thank you from the bottom of my heart :*>

Looking back now, I realise how much I have learnt and grown from this experience. I also want to give myself a pat on the shoulder for staying strong throughout all the things that happened during this project. If Phong in the future is reading: Don't ask "Can I do this" but ask "How to do it"; Be patient, respectful, and kind to others; Always ask for help if you cannot figure out something – you're not alone; And most importantly, don't forget to enjoy every single moment, no matter good or bad, because you only have once chance to experience it in life.

Helsinki 20.05.2021, Phong Truong.

Relation to KONE

The author conducted this research inside the KONE Technology and Innovation unit, to which he was related by a contract as thesis worker. In particular, he belonged to the Research team which is responsible for conducting research and innovation in KONE. The thesis is a part of KEKO – a Smart Building Ecosystem project (https://kekoecosystem.com/). KEKO is funded by Business Finland and founded on a consortium of 7 members: KONE, Nokia, YIT, Caverion, Halton, VTT and Netox. Its goal is to create the global standard in building data ecosystems and a smart platform for other parties to tap into. The platform will enable the collection, analysis and automatic application of data in building maintenance and design. The collaboration in the KEKO project not only occurs between the founding members but also with start-ups and SMEs (Small and Medium-sized Enterprises).

About KONE

At KONE, our mission is to improve the flow of urban life. As a global leader in the elevator and escalator industry, KONE provides elevators, escalators and automatic building doors, as well as solutions for maintenance and modernization to add value to buildings throughout their life cycle. Through more effective People Flow®, we make people's journeys safe, convenient and reliable, in taller, smarter buildings. In 2020, KONE had annual sales of EUR 9.9 billion, and at the end of the year over 60,000 employees. KONE class B shares are listed on the Nasdaq Helsinki Ltd. in Finland.

Abbreviations

AEC	Architecture, Engineering and Construction
AR	Augmented reality
BIM	Building information modelling
CAD	Computer-aid design
CSE	Customer Solution Engineer
IPD	Interpupillary distance
MEP	Mechanical, Electrical and Plumbing
SI	International System of Units
VE	Virtual environment
VR	Virtual reality

1 Introduction

The unique nature of the architecture, engineering and construction (AEC) industry requires extensive communication between several stakeholders such as owners, contractors, engineers and architects in different phases of a project (Wen & Gheisari, 2020). Evidence has shown that such communication in the industry is often inefficient (Zhang et al., 2020). This issue has been a source of conflict between contractor and client, resulting in poor performance and putting more than 10% of cost of each 1 billion US dollar worth project at risk (Wen & Gheisari, 2020). Many reasons to this communication challenge have been found. First, the working atmosphere in construction projects is often fragmented due to significant differences in organisational processes of each stakeholder, which hinders the collaboration between them (Du, Shi, et al., 2018). Second, the separation of the design and construction process in the industry caused by the current communication practice has led to ineffective information exchange between stakeholders, misunderstanding of the design, and potentially defects (Y. Chen & Kamara, 2008). Third and most importantly, the main communication means throughout the project life cycle in the AEC industry are still paper-based drawings. This inefficient communication media is considered as the major constraint and could result in delayed response to frequently overlooked design issues (Wen & Gheisari, 2020).

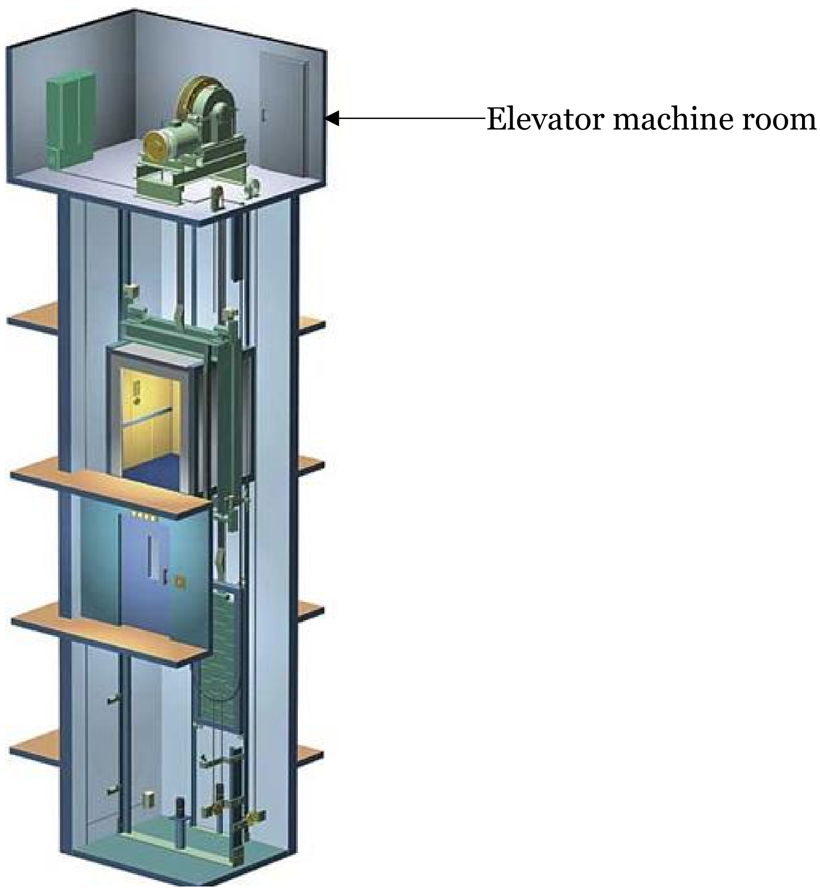

Figure 1. Elevator machine room in a typical elevator system (Makaa, 2017)

The use of 2D drawing, both in paper and digital format, has been a critical challenge in the life cycle of elevator project in high-rise building, especially for the design and construction of machine room (Figure 1). High-rise elevators are ones capable of travelling 240 m/min or 4 m/s. Only basic machine room designs are in standard layout drawings which are the typical submittals for elevator construction project. The layout design contains only major components and other critical parts such as trunking, cable routing, some electrical cabinets and other subcontractor equipment are missing. The current machine room designs do not have enough details for complex installation planning and collaborative design review by different stakeholders in the project. Hence, installation errors remain a critical issue, causing safety hazard, rework, delay and equipment unreliability. As both engineering complexity of construction project and client's expectation in quality are steadily increasing, a better means of communication in the AEC industry is indeed needed (Du, Shi, et al., 2018; Wen & Gheisari, 2020).

During the last few years, Virtual Reality (VR) technology has captured significant attention of both academic scholars and industry players in construction projects. VR is considered to be among the major technologies contributing to digitising the construction industry in the era of Industry 4.0 (Wen & Gheisari, 2020). In fact, an increasing number of use cases of VR both in research and real-life project have been reported (Whyte & Nikolić, 2018; Zhang et al., 2020). The growing attention of VR is driven by the increasing implementation of building information modelling (BIM) practice in the industry (Du, Shi, et al., 2018; Zaker & Coloma, 2018). BIM-based VR has the great prospect in design visualisation to better understand the design complexity and enhance its communication (Wen & Gheisari, 2020; Zhang et al., 2020). Cloud-based multi-user VR, a VR system that support several users at the same time through cloud, has also gained more attraction thanks to its ability to support remote collaboration between stakeholders (Du, Shi, et al., 2018). Beyond communication, this technology is also seen as the innovative tool that improves the quality of the entire construction workflow (Du, Shi, et al., 2018; Pratama & Dossick, 2019; Whyte, 2003). The benefit of multi-user VR is more pronounced during the COVID-19 pandemic where lockdown requires remote working and collaboration in daily tasks in AEC firms such as BIM coordination (Syamimi et al., 2020). Nonetheless, the adoption of VR in the AEC industry is relatively slow compared to other industries (Noghabaei et al., 2020). AEC industry players should be more willing to adopt the technology to explore the full potential of this technology.

Research objective and approach

Realising the great potential of multi-user VR, this research in collaboration with KONE Corporation (later referred as KONE) aims to study the use of a cloud-based multi-user VR environment for collaborative elevator machine room planning, installation and maintenance. The scope of this project focuses on complex machine room planning in high-rise buildings via case studies. The objective of this thesis is to determine the benefits of the multi-user VR application in the current process from the user and business perspectives and how they correspond to the current challenges of the machine room planning process. Besides, the study also addresses how to properly adopt multi-user VR in the current process through identifying potential use cases, users, requirements, and limitations. Four real-life high-rise elevator projects from KONE in the United States (US), the United Arab Emirates (UAE), Malaysia, and Indonesia were the pilots to be studied. Participants in this study are

AEC professionals from KONE and most importantly the project team members of the proposed pilots.

This study utilises the Design Thinking model proposed by Stanford Design School (Micheli et al., 2019) as the research framework. The critical emphasis is on the user-centricity in developing the VR environment based on user insights. Essential design thinking methods including interview and observation are used to collect user insights. A user testing is also conducted to evaluate the and generate improvement suggestions for the adoption of multi-user VR in the elevator machine room planning, installation, and maintenance. Moreover, the VR environment used in this study is built based on a commercial design VR software – DesignSpace. The software is developed by 3DTalo - a Finnish start-up that offers VR and AR solutions to business. It is also crucial to know that all interviews and user tests in this study are performed remotely due to the emerging COVID-19 situation.

Research questions

Based on the determined objectives, three research questions are established as the following:

- **Question 1**: What are the challenges of the current machine room planning, installation, and maintenance?
- **Question 2**: What are the benefits of applying multi-user VR from the user and business perspective in the current machine room planning, installation, and maintenance?
- **Question 3**: How multi-user VR should be applied in the current machine room planning, installation, and maintenance?

The first question serves as a starting point to gather insights of the current challenges to feed into the design of the VR environment and the user testing procedure. The second question addresses the core objectives of this study in finding the benefits of VR and suitable approach to apply the technology. The last question looks for when to use VR, whom to be involved, and critical requirements that facilitate the successful VR adoption in the current workflow.

Structure of the thesis

The first chapter has introduced the motivation, objectives, approach, and questions of this study. Chapter 2 presents a literature review on related work on the adoption of VR technology in both AEC academia and the industry from design to construction phase. Chapter 3 describes the methodology in data collection and analysis as well as details the practical implementation of this research. Chapter 4 then summarises the empirical findings obtained through collected data. Chapter 5 discusses those findings and connect them with the literature review to provide insights around the research questions. Finally, chapter 6 concludes the study by providing final answers to the research questions and suggestions for future study in the field.

A note on the term "Front-line" at KONE

KONE as an organisation comprise of the KONE Global company and KONE country-specific companies. The country-specific companies are often referred in KONE as front lines. This definition of a front line, which covers for example sales, maintenance operation, installations, administrative work, and customer service, is used throughout this thesis. It is important to note that this definition is different than the usual description of the front line as just a part of a business that has direct interaction with customers or other service recipient (Bélanger & Edwards, 2013; THE FRONT LINE | Definition in the Cambridge English Dictionary, n.d.).

2 Literature review

This chapter provides insights on the adoption of VR in the AEC context. Initially, section 2.1 provides a definition of VR and multi-user VR which has been used to conduct literature review. Next, section 2.2 highlights the common academic and commercial uses of VR in the AEC from design to construction phase. Section 2.3 provides a summary on the perceived and economic benefits of VR and multi-user VR. Section 2.4 discusses the limitations that hinders the adoption of VR while section 2.5 summarises potential requirements to foster it in construction projects.

2.1 Virtual Reality and Multi-user Virtual Reality

The history of VR dated back in 1950s when Morton Heilig developed the Sensorama multi-sensory simulator that had all features of an virtual reality environment but was not interactive (Bashabsheh et al., 2019). In 1968, Ivan Sutherland constructed The Sword of Damocles – the first true VR system that had a head mounted display with appropriate head tracking (Gigante, 1993). The term Virtual Reality was later introduced in the late 1980s by Jaron Lanier (Bailey & Bailenson, 2014; Bashabsheh et al., 2019; Fuchs & Guitton, 2011). Since then, extensive research into this technology has been conducted. However, no official definition has been accepted, as the terminology to describe VR is still evolving (Blade & Padgett, 2014). There is a lack of standard that defines not only the terminology but also technical requirements regarding VR (Brennesholtz, 2018). Brennesholtz noted several active projects to develop VR-related standards for better communication among researchers and industry players. Though Blade & Padgett (2014) indicates that the term VR remains elusive, Fuchs & Guitton (2011) concludes the importance of defining it to better communicate and unlock all possibilities of the technology.

The majority of VR definitions originate from the technical point of view (Fuchs & Guitton, 2011; Steuer, 1992) and are often used synonymously with the term Virtual Environment (VE) (Blade & Padgett, 2014). When describing VR, both academic scholars (Bell, 2002; Blade & Padgett, 2014; Whyte & Nikolić, 2018) and industry players (VR Industry Forum, 2017) refer to the use of computation technology to create an immersive virtual world, the emphasis for high level of interactivity, and the invocation of the human sensory system for a higher level of perceived realism. Steuer (1992) offers another approach by using presence and telepresence to define VR. However, the proposed method seems not inclusive enough because it does not cover the technology required to create VR. Besides, the former approach is more widely accustomed in both academic and industrial communities.

Therefore, this research utilises the definition of VR adopted from Fuchs & Guitton (2011) and summarized by Zhang et al. (2020) as:

"the uses of **computer science** and **behavioural interfaces** to simulate the behaviour of 3D objects in **a virtual world**, enabling **real-time interactions** with each other in **pseudo-natural immersion** via sensorimotor channels".

Firstly, this definition addresses the crucial hardware and software that enables the creation of the environment in VR. Secondly, the inclusion of behavioural interfaces explain that users perceive the computer-generated VE through sensorial interfaces (ordinary human senses) and the generator of the VE captures their activity in the environment through motor interfaces (hardware and software). Thirdly, the definition emphasizes the need of real-time interaction achieved via the no-lag-perception from the users. Lastly, the term pseudo is used instead of fully natural because the immersion level is subjective and dependent on the quality of the VR application and facility. A typical VR system (Figure 2), which aligns with this definition, includes the hardware, software, input and output devices, and users (Whyte & Nikolić, 2018).

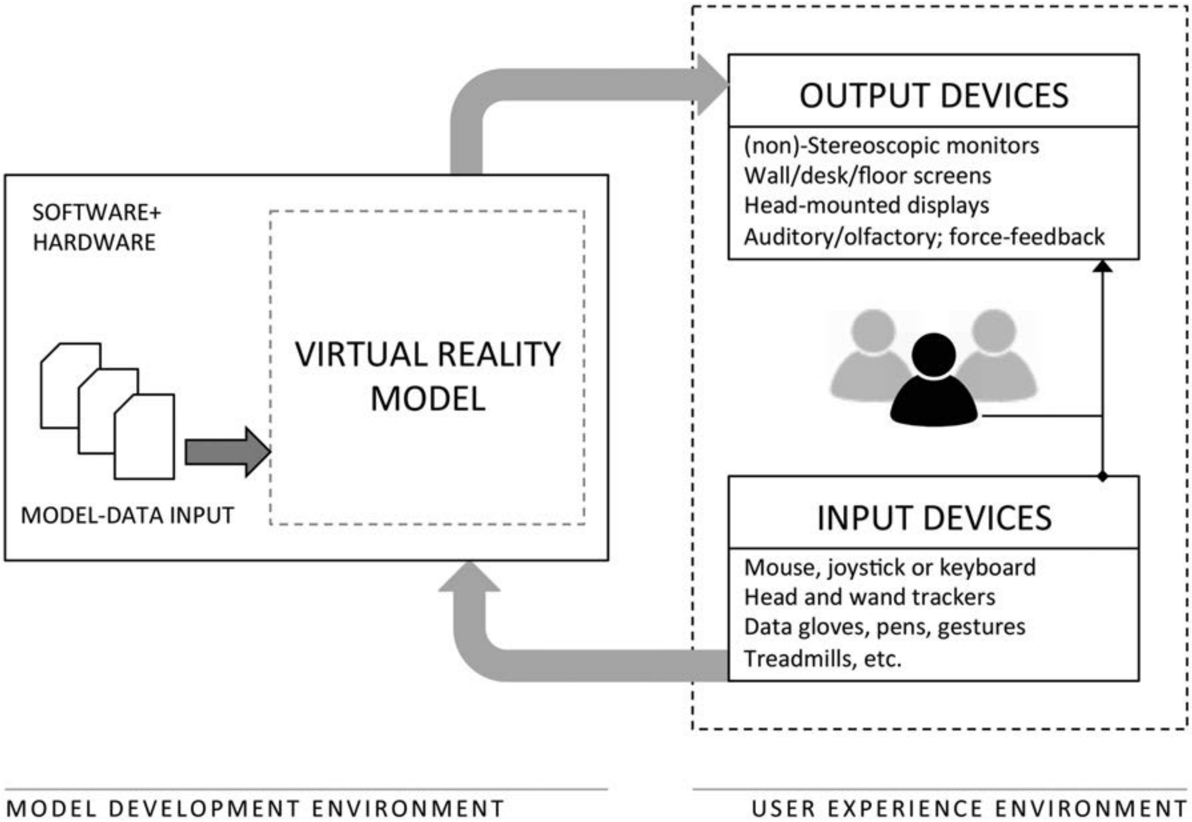

Figure 2. Components of a typical VR system (Whyte & Nikolić, 2018).

The extent of interaction in this definition is extended to beyond one user. The inclusion of several users is the critical additional element that coins the term multi-user VR or so-called collaborative VR as in Whyte & Nikolić (2018) and Bailey & Bailenson (2014), respectively. Hence, multi-user VR is the VR technology that allows several users to simultaneously experience and interact with the objects and with each other in a shared virtual environment (Bailey & Bailenson, 2014; Benford et al., 2001; Whyte & Nikolić, 2018). In the multi-user VR system, users' identity and activities are conveyed through an avatar as the graphical embodiment (Bailey & Bailenson, 2014; Benford et al., 2001). This embodiment through avatar allows users to interact with objects in the virtual environment and communicate with each other through several media such as audio, graphical gestures, text, etc. (Benford et al., 2001).

In a wider technical spectrum in the field, the Virtuality continuum concept (Figure 3) by Milgram & Kishino (1994) has been widely accepted to explain the various types of virtual and augmented reality (Whyte & Nikolić, 2018). Towards the left of the continuum address an environment that comprises of real-world scene. This environment can be directly observed by the person or via windows and 2D display. Toward the right of the continuum is the environment that solely consists of virtual objects. This environment, either immersive or non-immersive, is often created by computer graphic simulations. Mixed Reality environment is defined as an environment that has both real world and virtual objects inside. This environment involves any technologies between the extrema of the continuum. (Milgram & Kishino, 1994)

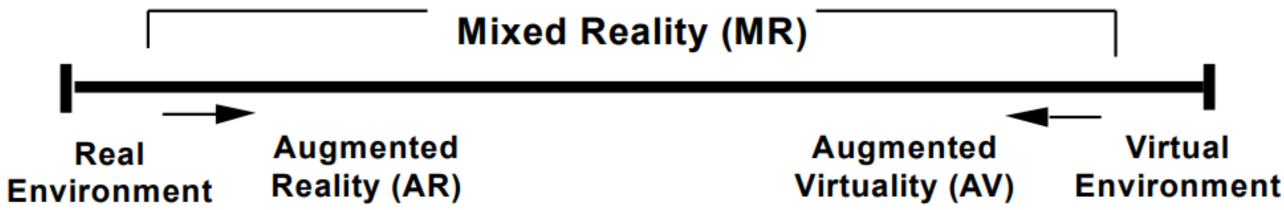

Figure 3. A simplification of the virtuality continuum (Milgram & Kishino, 1994).

2.2 The use of VR in AEC industry

VR and other mixed reality technologies have been successfully adopted in many industries such as manufacturing, military, and especially medical (Balali et al., 2020; Mosadeghi et al., 2016; Noghabaei et al., 2020; Stone & Hannigan, 2014). Though the benefits of VR in the AEC industry have been reported, the VR adoption rate in AEC has been very slow compared to other industries (Balali et al., 2020; Noghabaei et al., 2020). Nevertheless, there has been a significant increase in the use of VR/AR from 2017 to 2018 with considerable growth for VR/AR adoption in the next 5 to 10 years (Noghabaei et al., 2020). In the general industrial context, Syamimi et al. (2020) summarises the VR as means of communication, collaboration, coordination, visualisation, and training. In the AEC context, Bhoir & Esmaeili (2015), Li et al. (2018), Wen & Gheisari (2020), Whyte & Nikolić (2018) and Zhang et al. (2020) provides extensive overview on the use of VR via both academic and commercial lenses.

2.2.1 Usage in design phase

VR has been used to communicate and visualise design in the AEC industry (Wen & Gheisari, 2020; Whyte & Nikolić, 2018; Zhang et al., 2020). VR enables the creation of full-scale, immersive, and interactive virtual VR environments to identify critical design issues (Dunston et al., 2010). For instance, an early study by Woodward et al. (2007) has demonstrated successful use cases of various mixed reality technologies in architectural planning of a real-life building project. Balzerkiewitz & Stechert (2020), Ozcan-Deniz (2019) and Whyte & Nikolić (2018) point out that design review is the main application of VR in the AEC industry from 2010 to 2019 while Wen & Gheisari (2020) concludes 41% of the articles reviewed in their studies addressed the same usage. Interestingly, Building Information Modelling

(BIM) integration with multi-user VR using game engines such as Unity is gaining more popularity in the AEC (Du, Shi, et al., 2018; Wen & Gheisari, 2020; Whyte & Nikolić, 2018; Zaker & Coloma, 2018). It helps to facilitate design collaboration between stakeholders since outsourcing complicated design to international vendors and having project teams with diverse geo-location are common practices in AEC firms (Bryant, 2006; Nayak & Taylor, 2009). Syamimi et al. (2020) emphasised the benefits of multi-user VR for remote collaboration in the wake of Covid-19 pandemic. Nevertheless, Wen & Gheisari (2020) concluded that the majority of cases in this application adhere to user involvement rather than co-design. In other words, it focuses more on involving clients and end-users in pre-construction and post-occupancy evaluation via building walk-through (Otto et al., 2005; Pratama & Dossick, 2019; Wen & Gheisari, 2020; Zimmerman & Martin, 2001). Most importantly, VR in design review is mainly used in complex projects such as airports and healthcare facilities (Noghabaei et al., 2020; Whyte & Nikolić, 2018; Zhang et al., 2020). A study on how lead user firms in the construction sector in USA and UK used VR by Whyte (2003) concludes similarly but also finds VR usage in small projects with design reuse.

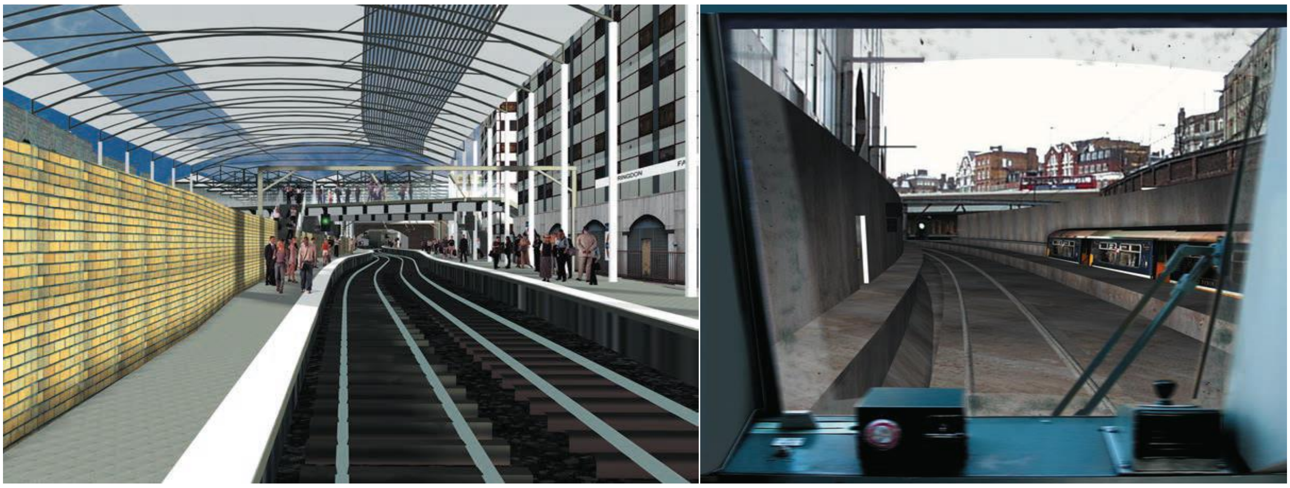

Figure 4. VR simulation in the train line Thames-link 2000 (Whyte & Nikolić, 2018)

Whyte & Nikolić (2018) provides many real cases that used VR for design review in the industry. Bechtel Visual Technology Group created many VR environments from CAD for the Dubai International Airport, the London Luton Airport, and the train line Thameslink 2000 project in London to collaboratively review critical safety requirements between designers, contractors and the end-users. In addition, COWI (2019) has recently reported the use of VR to review the arrangement of signage in the new development of Copenhagen Airport's new Pier E. COWI also remarks on VR usage for walk-through review in the expansion of Stavanger University Hospital (Stavanger - Norway) and the placement of new machinery in Vestforbraending waste treatment plant (Glostrup – Denmark). Du et al. (2017), Du et al. (2018), Gu et al. (2011) and Kähkönen et al. (2007), for instance, proposed different cloud-based multi-user BIM-to-VR systems that enable remote collaboration between internal and external stakeholders. A study by Zaker & Coloma (2018) investigated a VR-based workflow in a real construction project in Barcelona where the project team collaboratively conducted design review and decision making in the BIM-originated virtual building.

Yamamoto et al. (2018) has developed a VR-teleconference environment that allows all stakeholders to hold meetings, modify and track all design changes to the 3D objects.

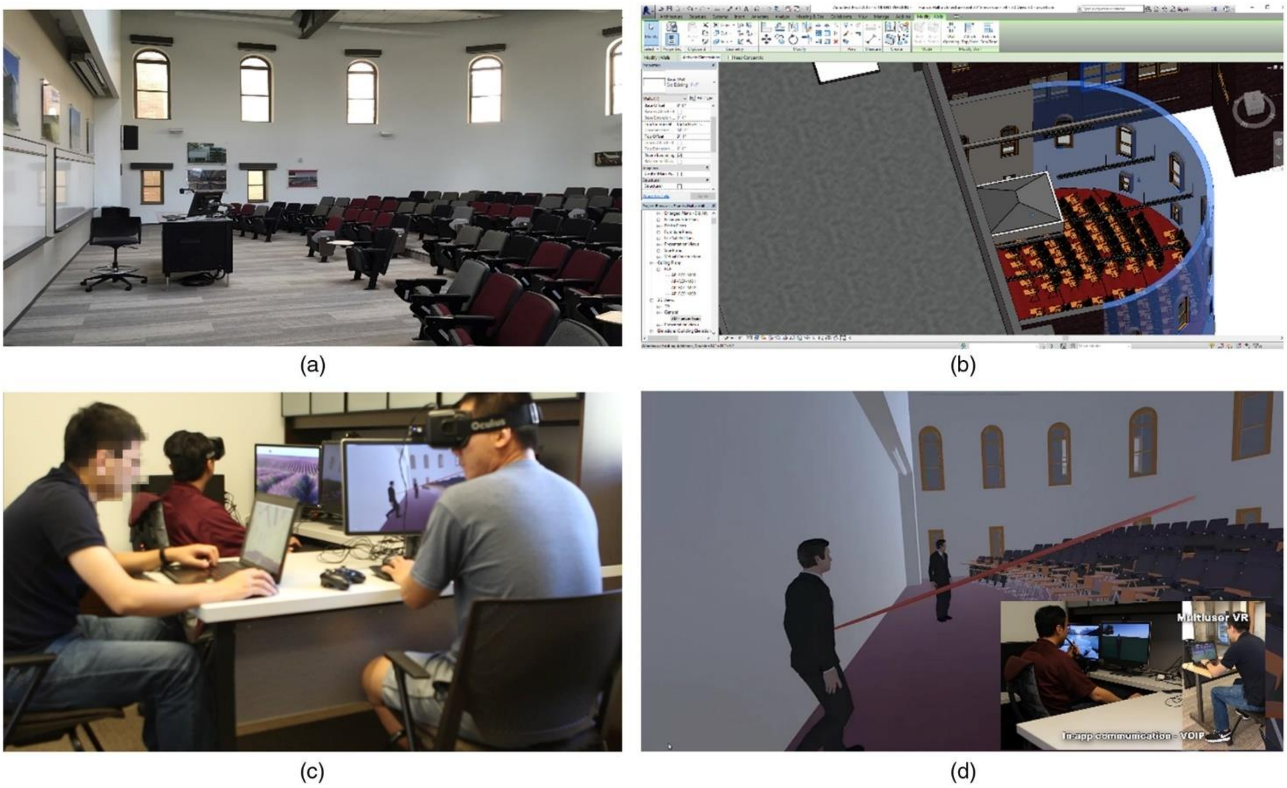

Figure 5. The use of CoVR (collaborative BIM-VR): a) the original physical scene; c) users use VR headset; b) and d) immersive virtual scene in CoVR system with VOIP (Du et al., 2018)

VR has also been utilised in many study experiments to identify human behaviour in the built environment (Gu et al., 2014; Whyte & Nikolić, 2018; Zhang et al., 2020). One of the key benefits of VR is that it enables a high level of safety, immersion, and control testing environment (Zhang et al., 2020). In this application, a simulation of an emergency such as fire or earthquake in a built environment is conducted by VR. Wayfinding and emergency behaviour is among the most common study topics (Whyte & Nikolić, 2018; Zhang et al., 2020). For instance, Mossberg et al. (2020) and Andrée et al. (2016) studied the willingness to use evacuation elevators in case of fire in a high-rise building and under a deep metro station, respectively. Both studies aimed to address conventional evacuation challenges such as fatigue due to climbing many stairs and difficulties for people with disability.

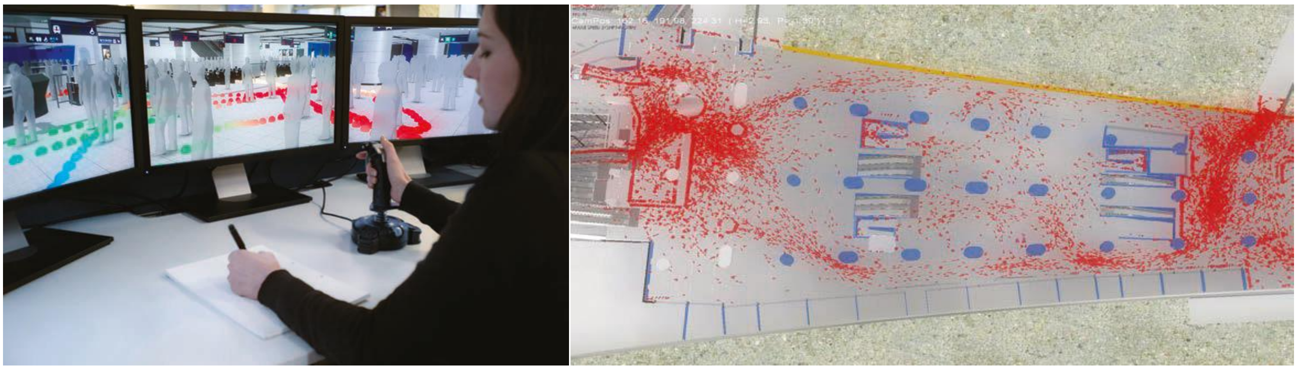

Figure 6. Arup's specialist is analysing the journey recorded in the VR simulation of the Admiralty Metro Station in Hong Kong (Whyte & Nikolić, 2018).

Beyond research, VR-enabled experiments are also used to train and feed into the iterative design process. Lovreglio et al. (2018) developed a VR series game VR environment to study and train people in the case of an earthquake in a hospital in Auckland. Kinateder et al., (2019) studied which colour of emergency exit sign is most recognised and proposed the changes in design of the evacuation system. Flor et al. (2021) studied user acceptance of Ethylene-tetrafluoroethylene (ETFE) double skin facade in office buildings via VR and derived an interactive design for the material. Havard et al. (2019) utilised VR to understand customers' movement and design the most optimal industrial shop floor layout. For commercial uses, Arup, an engineering and design firm, used VR to study the impact of signage on commuter's wayfinding in a new extension of the Admiralty Metro Station in Hong Kong (Whyte & Nikolić, 2018). Through analysis of users' feedback and recorded journey in VR, 25% of the signage was suggested to be relocated or modified, and half of the suggestions were implemented by the client.

2.2.2 Usage in construction phase

VR has been referred to as a method for visualisation of field construction planning (Lu & Davis, 2016). The urgency of using VR or other mixed reality is from the inefficient conventional construction management which utilises complex graph-based data for spatial-temporal planning (Whyte & Nikolić, 2018). As construction progress is not constant, a more visualised way to quickly plan and communicate construction tasks is needed. Abdelhameed (2012) performed a study on visualising all schedule changes in VR and found it beneficial in construction scheduling and reporting. A recent study by Getuli et al. (2020) developed a BIM-VR system that allows users to intuitively plan details of the construction layout. Rekapalli & Martinez (2009) developed a VR system where contractors can simulate sophisticated discrete-events like bad weather and experience the consequence of such events on the construction site. Contractors, therefore, can reduce or avoid delays by creating accordingly contingency plans. Besides, Whyte & Nikolić (2018) indicated a real use case where a detailed 4D model of the construction site of a 62-storey tower (22 Bishopsgate) in London with 4200-activity schedule was embedded in VR to conduct site logistic planning. Whyte & Nikolić (2018) also reported Mortenson Construction, a construction and real estate development in USA, integrated VR into its workflow on the Walt Disney Concert Hall project in Los Angeles for construction planning. Rekapalli & Martinez (2009) and Xie et al. (2011)

took a further step to incorporate RFID and a cyber-physical system in VR to simulate real-time changes onsite for the physical facility on the virtual models for better decision-making process.

Figure 7. Users are using the immersive VR to create and review the site safety and logistics plan in the construction of 22 Bishopsgate tower in London (http://www.freeform3d.co.uk/22-bishopsgate)

The use of VR for construction safety planning, training, and monitoring has also gained considerable attention in the research community and the industry (Du et al., 2018; Zhang et al., 2020). Safety planning often exists under drawing or heuristic knowledge while construction sites are complicated with unpredicted safety risk surrounding (Zhang et al., 2020). Hence, site personnel have difficulties in fully comprehending the working area and making immediate risk assessment. Despite the proven benefits from research, real use cases for VR in safety training are still limited or not reported in literature. Bhoir & Esmaeili (2015) report none of any safety training organisations that it surveyed in the US used virtual reality. A recent study by Ozcan-Deniz (2019) on 18 USA-based companies in the construction industry has yielded a similar result. AR, in this type of application, tends to have a wider adoption than VR (X. Li et al., 2018; Whyte & Nikolić, 2018).

However, VR in construction safety has been extensively explored by researchers. For instance, Hadikusumo & Rowlinson (2004), H. Li et al. (2012) and Perlman et al. (2014) created a virtual environment for users to experience the working environment with prompt safety messages via VR walk-in. Similar studies by (Lu & Davis, 2016, 2018) were also conducted with sound from the construction site added to stimulate a higher level of realism in hazard identification training. Besides, inadequate collaboration among workers is among the most influential factors that cause accidents on the construction site (Zhang et al., 2020). To that extent, multi-user VR was also implemented in studies by H. Guo et al. (2012) and H. Li et al. (2012b) that allows users to collaborate in general safety training and how to safely dismantle tower cranes, respectively. Cheng & Teizer (2013) and Fang et al. (2014) took multi-user VR further by embedding real-time data in the physical site by tracking sensors into the virtual world with hazard identification algorithms for automatic onsite monitoring.

2.3 The perceived and economic benefits of VR

The benefits of VR in the AEC industry have been proven and summarised by many critical literature reviews (Bhoir & Esmaeili, 2015; X. Li et al., 2018; Wen & Gheisari, 2020; Zhang et al., 2020). These reviews indicate that the advantages of VR depend on different use cases when applied properly. Understanding why VR is beneficial requires the need to address its characteristics (Bailey & Bailenson, 2014). As a medium to convey message, VR has four main characteristics: interactive, spatial, real-time, and physical presence (Bailey & Bailenson, 2014; Dunston et al., 2010; Whyte, 2002). From the definition used in this work, it can be implied that multi-user VR inherits all characteristics and benefits from the conventional single user VR. Nonetheless, Bailey & Bailenson (2014) argue that the system construct of collaborative VR added three more unique characteristics: co-presence, self-presence, and embodiment.

2.3.1 Perceived benefits of VR

The interactive, spatial and real-time properties of VR have improved the communication of the design between designers with other stakeholders through immersive visualisation. VR enables the creation of full-scale, immersive, and interactive virtual VR environments, in which users' movements are intuitive and not restricted (Dunston et al., 2010; Zaker & Coloma, 2018). Details of each component are delivered via a user-friendly interface (Zhang et al., 2020). Whyte & Nikolić (2018) indicated the effortless spatial comprehension given by the real scale model in VR, which was deemed as an impressive feature by the participants in (Zaker & Coloma, 2018). Though CAD and BIM have been increasingly adopted to 3D-model architectural drawings, they are often too complicated for non-engineering stakeholders with limited spatial understanding (Wolfartsberger et al., 2018; Zhang et al., 2020). Instead of speaking from abstraction, it hence becomes a tangible frame of reference that reduces the understanding gap or even eliminates design misunderstandings between designers (visual thinker) and other stakeholders (non-visual thinker) (Zaker & Coloma, 2018; Zhang et al., 2020).

Besides, the strong physical presence as "being inside the building" brings a significant level of immersion that users may not be able to experience in other mediums (Zaker & Coloma, 2018). Cumulative evidence through studies in the AEC industry justifies the statement (Andrée et al., 2016; Balali et al., 2020; N Gu et al., 2014; Lovreglio et al., 2018; Mossberg et al., 2020). With such immersive and visualised experience, users often generate better decision-making in the early design stage where various design alternatives need to be considered (Zhang et al., 2020). Bailey & Bailenson (2014) pointed out that immersive VR enables users to unexpectedly provide nonverbal feedback, resulting in more fruitful discussions in end-user involvement review. For instance, study by Maftei & Harty (2015) concluded that users were able to detect several non-conformances to client's request by combining both verbal and non-verbal behaviours when conducting design review. Whyte & Nikolić (2018) reported another case where a crossrail engineer successfully described a design conflict by using hand gestures, which was difficult to notice on the plan view and to only verbally explain. Beyond physical presence, real-life physical and psychological responses can also be induced in VR (Bailey & Bailenson, 2014). Study experiment performed by N Gu et al. (2014) and Zou et al. (2017) on the impact of immersive VR on the end-user feedback conclude similarly. VR can hence serve as a pre-construction mock-up where AEC professionals can effectively and accurately plan site logistics and especially test out the safety level of the future working site (Zhang et al., 2020). Perlman et al. (2014) report that workers performed better in critical risk identification such as object falling or carrying a heavy load. Other studies indicate that most users identified more risk and formed immediate risk-aversion mechanisms in VR-based training than those that had conventional training via photographs or documents (Hadikusumo & Rowlinson, 2004; H. Li et al., 2012a; Lu & Davis, 2016, 2018).

With the increasing number of virtual teams in the AEC industry, multi-user VR not only provides benefits as mentioned above but also facilitates and enhances the collaboration between stakeholders. Multi-user VR is found to be the most effective way to connect remote stakeholders virtually (Du, Shi, et al., 2018). Participants in Kohler et al. (2011) indicate the feeling of being in the same environment with others via synchronously shared context established a relationship among participants to a certain degree. Zhang et al. (2020) implies similarly with the emphasis on co-presence reinforcing collaboration among participants by bringing more real-life social aspects like mutual learning and encouragement. Enhancing collaboration between clients and end-users in immersive VR means more participation from them in the design process, which helps avoid over-designed mechanisms that cost more to operate while increasing client's satisfaction by meeting their requirements (Otto et al., 2005; Ozcan-Deniz, 2019; Wen & Gheisari, 2020; Zimmerman & Martin, 2001).

Multi-user VR comes in much useful nowadays when everybody is working remotely due to the pandemic COVID-19 (Syamimi et al., 2020). Overall, multi-user VR fulfils the key elements of an effective remote collaboration: shared context, awareness of others and clear communication (Bailey & Bailenson, 2014). Unlike the most common form of remote collaboration - video conferencing, multi-user VR draws more attention from the users with the act of wearing the VR headset and being separated with the real world (Zaker & Coloma, 2018). In addition, study by Anderson et al. (2017) point out that verbal communication was made easier in collaborative VR because of the ability to utilise deictic references like "here", "this", "there" etc. The study also indicated non-verbal information was also effectively communicated via avatar movement and position even if done unintentionally, which complemented the deictic verbal communication. Moreover, multi-user VR can minimize misunderstandings and reduce communication cost in facility management where often the onsite maintenance technician and building designers are not in the same location (Shi et al., 2016). When comparing with face-to-face meeting for BIM coordination, study by Abbas et al. (2019) yields an insignificant statistical difference of BIM meeting in collaborative VR regarding discussion quality and the richness and openness of the communication. The embodiment property of VR, which could provide digital equivalent to face-to-face communication, may account for such results (Bailey & Bailenson, 2014). The finding is also complemented with the feeling of being there together reported by the participants in Anderson et al. (2017) thanks to the use of avatars in virtual environments.

2.3.2 Economic benefit of VR

The perceived benefits of VR in the AEC industry have been well-examined (Chapter 2.3.1). However, there is a lack of studies on the economic benefits of VR in the industry (Noghabaei et al., 2020; Pratama & Dossick, 2019). Data on the actual cost-saving is, therefore, limited. Nonetheless, a recent study by Ozcan-Deniz (2019) on the use of VR in 18 US construction companies has found direct cost and time saving in 93% of the projects. The use of virtual mock-ups mostly accounts for economic benefits of VR throughout the life-cycle (from planning to decommissioning) of construction projects (H. L. Guo et al., 2010). Direct cost-saving derive from the replacement of costly-physical mock-ups by virtual ones. VR VR environment of several medical building projects studied in Ozcan-Deniz (2019) requires 15% less implementation cost compared to physical ones. Layton, a US construction firm, has saved 90% of construction mock-up cost by using VR to replace 20 physical ones which were required for the owners and end-users to experience (McGlothlin, 2018).

Ozcan-Deniz (2019) has also pointed indirect economic benefit of using VR to visualise design and improve collaboration and communication within the project team. VR offers similar sense of presence found in physical VR environments to evaluate numerous design alternatives effectively and efficiently (Flor et al., 2021; N Gu et al., 2014). Through virtual walk-in, project team can view the design from many perspectives, reducing unexpected design changes and error in the construction phase (Haggard, 2017; Ozcan-Deniz, 2019). A British railway company reports saving millions of pounds thanks to the investment in VR software for design review which helps to identify critical safety issue and speed up track improvement (Whyte & Nikolić, 2018). A study on applying virtual prototyping in the construction phase for process simulation in real-life projects in Hong Kong reports up to 12% and 17% in cost and time saving, respectively (H. L. Guo et al., 2010). Moreover, Havard et al. (2019) has recognised that participants can already improve the shop layout during a 30-minute-session of design review in VR which reduces 20% of walk distance and 6% of completion time in their study. Most recently, a study by Syamimi et al. (2020) on the use of VR for remote BIM coordination in three Singaporean construction firms as an response to COVID-19 has reported up to 4 working days of time saving, up to 10000 Singaporean dollars (approximately 62000 euros according to the exchange rate on 2 Feb 2021) in cost saving, and an increase of 50000 Singaporean dollars (approximately 31000 euros according to the exchange rate on 2 Feb 2021) in sales revenue.

VR also reduces the cost and time for travelling and lodging participants in a diversely located teams in the AEC industry (Bryant, 2006; Nayak & Taylor, 2009; Pratama & Dossick, 2019; Syamimi et al., 2020). This benefit is even more pronounced during the COVID-19 pandemic as travelling cost, time, and risks are minimized (Pratama & Dossick, 2019; Syamimi et al., 2020). For instance, Siemens has utilised the virtual mock-up to provide one of its clients expert maintenance training remotely in VR since the client is located offshore (Boyd & Koles, 2019). Boyd and Koles report the reduction of two to three days of training to 45 minutes as well as the scheduling challenges for everybody to be at the same time and place. This example also amplifies the future economic benefit of the reusability of VR mock-up, which is noted in Whyte (2003).

Figure 8. Persimmon Homes development VR model (Whyte & Nikolić, 2018)

Even though the highest economic benefits of virtual prototyping are in design and construction phase (H. L. Guo et al., 2010), VR also brings business values in sales and marketing phases to AEC firms. VR is still considered as novel in the AEC industry and its adoption results in the glossy image of the firm (Whyte & Nikolić, 2018). For companies with innovation as a business value proposition, adopting VR is beneficial. For instance, BNBuilders, a US construction engineering company, has gained more contract awards by marketing their VR usage in projects to enhance their technological innovative image in the market (Haggard, 2017). Housing developer Persimmon Homes has given the public a VR tour of its new apartment blocks in Sheffield, which attracted local news coverage and promoted sales even when the construction has not begun (Whyte & Nikolić, 2018). In addition, online non-immersive VR model has also been used by Munich Airport Center to advertise rental space to potential customers (Whyte & Nikolić, 2018). This way of advertising is cost-effective as the venue furnishing can be quickly done and helps to reach more clients internationally.

2.4 The limitations that prevent VR adoption in the AEC industry

Interoperability issue between VR software and BIM data is the most significant limitation that hinders the adoption of VR in the AEC industry (Du et al., 2018; Ozcan-Deniz, 2019; Zhang et al., 2020). In common BIM-VR software, BIM acts a data source that contains many data types such as building elements, materials, cost, etc. that are based on the Industry Foundation Class (IFC) (Chen et al., 2005). Only elements' material, geometry, and relationship from BIM (.ifc) model are transferred to a Filmbox (.fbx) format to create 3D model for the VR environment (Du et al., 2018). The lack of VR standards defining a common technological implementation results in the non-robust transfer of BIM data into VR platform (Brennesholtz, 2018; Noghabaei et al., 2020; Ozcan-Deniz, 2019). For instance, one project team in Pratama & Dossick (2019) had to regain the texture of the 3D model lost when exporting it from Revit for later use in VR. In addition, common VR software in the market only focuses on reproducing building geometry and texture while no attention is drawn to transfer other important data such as element identification and cost (Du et al., 2018; Noghabaei et al., 2020; Pratama & Dossick, 2019). Du et al. (2018) also emphasises the lack of information exchange ability between VR and BIM. As decision-making process in the AEC industry is highly data-driven and not all data is always available, the inability to retrieve missing data can hinder the quality of communication through multi-user VR. Moreover, an easy and direct transfer of data generated in VR to most common BIM tool is not available, which requires additional step to integrate changes made in VR session to the original BIM model (Balzerkiewitz & Stechert, 2020).

Health and discomfort issues are also found as an usual disadvantage for VR users (Zaker & Coloma, 2018). Motion sickness is the most common issue when using VR with numerous factors influencing user's susceptibility to it (Stanney et al., 2020). A recent study by Stanney et al. (2020) report that interpupillary distance (IPD) non-fit is the major cause that has greater impact on female users. Females with IPD non-fit tend to experience more motion sickness than males and take more than 1 hour to fully recover after exposure. Comparing the IPD range support by common VR headset in the market (Stanney et al., 2020) with the IPD range of adult population (Gordon et al., 2014), only Sony PlayStation will fit the everyone but is not powerful enough for industrial use. Common headsets used in the industry such as HTC Vive cannot accommodate 35% females and 16% males while those number are 60% females and 50% males for Oculus Rift S. In addition to the VR headset, using less powerful computers that do not provide at least 60 frame per second (fps) also results in higher chances of motion sickness (Balzerkiewitz & Stechert, 2020).

Other limitations contributing to the slow adoption rate of VR are found. Even though CAD and BIM has gained more popularity in the AEC industry, their use in practice remains limited (Otto et al., 2005; Ozcan-Deniz, 2019). Since the quality of design review in VR relies on the accuracy and completion of 3D model, adopting VR in the workflow might not be feasible if subcontractors do not use BIM software (Ozcan-Deniz, 2019). Moreover, studies by Noghabaei et al. (2020) and Zaker & Coloma (2018) acknowledge the resistance of decision-makers to adopt VR in AEC firms as another major limiting factor. The lack of cost/benefit analysis in academic research and knowledge of VR technology from the upper management account for this challenge (Noghabaei et al., 2020). It is understandable that companies hesitate to invest in VR without knowing the exact implementation cost and savings. Adopting VR requires investment in BIM to create 3D model and VR-compatible hardware (Ozcan-Deniz, 2019; Zaker & Coloma, 2018). In addition, maintaining licenses to VR software is vital as in-house VR development is neither viable nor beneficial, which might be challenging for small-size companies (Ozcan-Deniz, 2019; Pratama & Dossick, 2019). Efforts and resources to train their personnel to use VR and especially keep up with the development of the tool must also not be neglected (Ozcan-Deniz, 2019). Consequently, this slow adoption from business with fragmented market has made it challenging for VR start-ups to acquire sufficient funding (Perkins Coie LLP, 2020). Such funding is critical for the technological development to meet the high requirements from businesses. A feedback loop is then created, which hinders the use of VR in the AEC industry.

2.5 The requirements for the adoption of VR

Evidence has shown that the collaboration experience in real world can be substituted by that in VR, given that the level of immersion is significant for participants (Morina et al., 2015). Therefore, VR hardware and software are required to support and increase the realism perception from the users. Regarding hardware, powerful computers capable of processing and displaying complex 3D model with low latency are required (Otto et al., 2005). Specifically, a constant frame rate of at least 60 fps or higher at 90 fps is needed as lower frame rate results in noticeable image lag, increasing the chance of users experiencing motion sickness (Balzerkiewitz & Stechert, 2020). Stanney et al. (2020) suggests that VR headset manufacturer should include adjustable IPD feature with a range of 50 – 77 mm to minimize motion sickness because the proposed range captures 99% of both females and males.

VR software should accommodate the design-to-VR process and address poor data synchronisation (Du, Zou, et al., 2018; Pratama & Dossick, 2019; Zhang et al., 2020). Real-time feedback to the user's interaction in VR is required and essential in facilitating the communication in design workshop (Havard et al., 2019). High latency can have negative impacts on the quality and efficiency of the decision-making process in construction project (Du, Zou, et al., 2018). VR tool must also facilitate the workflow structure in the AEC industry, ensuring importing and exporting in VR is highly compatible with current BIM tool (Pratama & Dossick, 2019). Exporting tool must ensure compatibility of the exported 3D model file with current CAD or BIM authoring tools to avoid additional conversion (Balzerkiewitz & Stechert, 2020; Zhang et al., 2020). Balzerkiewitz and Stechert also proposed a guideline on the how the tool should work as illustrated in Table 1.

Table 1. Requirements for exporting tool in VR sorted by priority in Likert scale (Balzerkiewitz & Stechert, 2020).

Requirements	Priority
The program must be useable with just a few clicks (<10)	5
The exporting object type is selectable	4
The transmission time is less than 10 seconds	4
The export is possible to different CAD program	4
The position of the object is automatically calculated	3

It is also important to tailor features to be included in VR that meet the need of each AEC company (Zaker & Coloma, 2018). The study performed by Zaker and Coloma mentioned only measuring and movement tool in VR, which could be deemed as essential in their case to review the design of a construction project. Studies by Balzerkiewitz & Stechert (2020) and Wolfartsberger et al. (2018) on product concept design and component design review, respectively, also provide many features that are deemed critical for their cases. The features proposed are illustrated in Table 2. However, it remains unclear how they achieve the priority ranking of the features, especially with the former study where A, B, and C ranking is determined.

Table 2. Required features in VR (Balzerkiewitz & Stechert, 2020; Wolfartsberger et al., 2018).

Features	**Priority** (Wolfartsberger et al., 2018)	**Priority** (Balzerkiewitz & Stechert, 2020)
Selecting an assembly group or part	A	-
Divide a group until reaching the lowest level	A	-
Selection must be clearly highlighted	A	-
Move and rotate groups and parts by "grabbing"	A	-
Move and rotate groups and parts along axes to simulate manipulation ("open door" or "pull lever”)	A	-
Hide and show groups and parts	B	-
"Teleport" function for huge scenes	B	-
Scaling of the 3D model	B	4
Show tools (e.g. screwdriver) instead of default controller	C	-
Sectional view of parts	C	-
Measuring tool for distances, diameters etc.	C	-
The object is available in a format that is exportable to CAD programs	-	5
The reference coordinate systems of all displayed components are visualisable	-	5
The shape of the generated objects will be selected using an object library	-	4
Created objects are related to other objects	-	4
Surfaces, edges, and nodes of the created objects are editable	-	3
The alignment of models is automatically based on edges and points	-	3

As design review in VR heavily depends on the accuracy and completeness of the 3D model, BIM practice should indeed be implemented in AEC firms. Beyond that, company must ensure important stakeholders in the 3D model creation process have similar BIM authoring tools (Ozcan-Deniz, 2019). Moreover, evidence has shown a large VR familiarity gap between the industry and academia with the latter having more awareness about the benefits of the technology (Noghabaei et al., 2020). Upper management and decision-makers should be educated about the technology and what it brings to the company. In addition, VR training should also be given to AEC personnel or at least VR specialist in the company to better integrate VR into the workflow (Ozcan-Deniz, 2019). Awareness factor is found to be critical to enhance the willingness to use VR in the AEC industry (Zaker & Coloma, 2018). The notion of VR adoption should be treated as an essential part of the project rather than as a novelty (Pratama & Dossick, 2019). There is also an urgent need for a cost-benefit analysis as well as clear business use case for the use of VR in both the academia and the industry (Noghabaei et al., 2020; Otto et al., 2005; Pratama & Dossick, 2019). They are deemed critical to help business acknowledge the economic value of VR as well as which type of and how VR can be applied in the current workflow of each company (Otto et al., 2005).

3 Methodology

This study utilises Design Thinking model of Stanford Design School, which is one of the most influential applied models of its kind (Micheli et al., 2019), as an overall framework. Design Thinking, in practice, is a methodology that fills innovation activities with a human-centred mindset with the aim of understanding what the end-users need and providing solutions to the root problem (Brown, 2008; Liedtka, 2015). This methodology has been widely adopted in the product development process in major organisations (i.e. Samsung, P&G, etc.) and used to solve the open, complex, dynamic, and networked nature of current challenges in the modern world (Brown, 2008; Dorst, 2015; Micheli et al., 2019). The model is non-linear process including five steps: Empathize, Define, Ideate, Prototype, and Test (Liedtka, 2015). Liedtka has also categorized the model into three main stages: (1) Collecting data about user need (Empathize and Define), (2) Generating idea (Ideate), and (3) Testing (Prototype and Test). A research procedure of this thesis is developed based on the model and illustrated in Figure 9. The goal of the first stage is to collect necessary understanding about the challenges of the current machine room planning process and user needs for VR adoption. The goal second stage aims to generate ideas on the development of the VR environment and the user testing procedure based on the insights gained from the first stage. The goal of the last stage is to build the VR environment and test it out with the end-user.

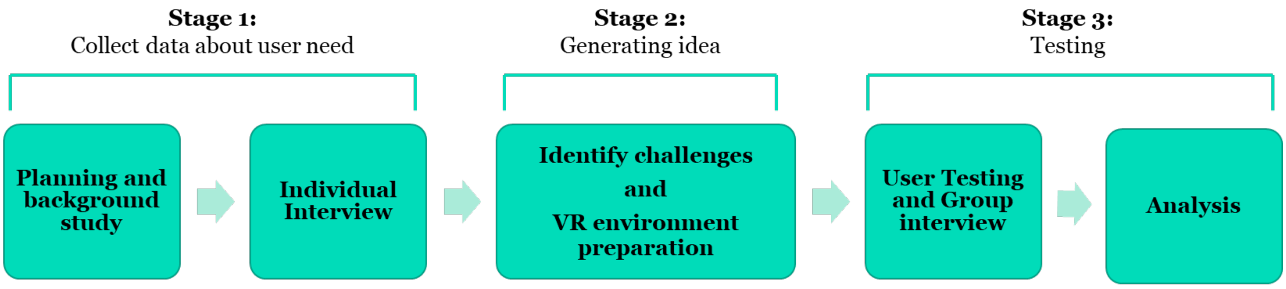

Figure 9. The research procedure.

The procedure embeds user-centricity and involvement at its core which is the fundamental feature of design thinking (Micheli et al., 2019). In Planning, a list of key stakeholders as potential users of VR and assumptions of current challenges in the machine room planning process was established. Interview questions were then developed, and potential interviewees were invited for the next phase – Interview, which are detailed in Section 3.1. Next, the interview responses were then analysed. Generated insights from the interview and the literature review were used for developing the VR environment and the user testing procedure. Key stakeholders, who are project team members of the testing pilots were invited to the next phase – User Testing. Details on the testing procedure and its practical implementation are indicated in Section 3.2. Finally, data generated from the user testing were then analysed in the last Analysis phase together with the interview response to address the research questions of this study. The analysis approach in this study is described in Section 3.3.

Table 3. List of stakeholders involved in the study.

Front line	Roles of participants
1	Project Manager Customer Solution Engineer Installation Supervisor Project Director[1]
2	Maintenance Manager Quality Control Engineer Customer Solution Engineer
3	Customer Solution Engineer Project Engineer Construction Manager Installation Manager Installation Supervisor Project Manager
4	Customer Solution Engineer (Senior) Field Support Engineer
5	Customer Solution Engineer Project Manager Installation Supervisor

1. referred as Project Manager later in text

Table 3 indicates all stakeholders involved in the interview phase before testing and in the user testing phase. In this thesis, the role of Project Director is referred as Project Manager to reduce the complexity of roles for the reader. Customer Solution Engineer is referred in its short form of CSE to avoid unnecessary lengthy sentences. Moreover, the manager role is sometimes referred as one of the managers when it is deemed not needed or there is a risk of revealing the participant's identity. Similar approach also applies to the role of engineer.

3.1 Individual interview before user testing

The goal of the interview was to find out (1) the current challenges of the machine room planning, installation and maintenance, (2) what the project team has done to tackle the challenges and their wishes to improve the process, and (3) their perception of VR and the use of VR in the process before user testing. The first goal addresses the first research question. The qualitative semi-structured interview is the method to collect insights from the interviewees. This method provides flexibility to adjust and formulate interview questions based on the interviewee's response to deepen the conversation. The interview session started with a warm-up section to help interviewees recall their experience with the current machine room planning process. Three sections with questions regarding the challenges, improvement suggestion and perception of VR before user testing followed. In the last section, interviewees were asked to indicate their expectation, viable use cases, and their requirements and limitations for the adoption of VR in the current machine room planning process.

There were 14 interviewees from four pilots and KONE Global company selected for the interview. Participants from Finland are former project team member of the pilot projects and KONE personnel having expertise in the field work. Details on the interviewees and their roles are disclosed in Table 5. There are two interview types: a 30-min-short-interview and a 1-hour-deep-interview. Both conduct all sections with the latter provides more time to deep dive into the consequences of the current challenges and the interviewee's viewpoint of VR and multi-user VR. The interviews were carried out remotely using Microsoft Teams a means of communication. Due to a language barrier, two interviews were conducted in a written format. In this case, two interviewees wrote down their answers based on the given questions to be translated for analysis.

3.2 User testing

The objective of user testing is to let potential users experience the use of multi-user VR in the machine room design review and planning process by replicating actual tasks in the current process. Due to the emerging COVID-19 restrictions, the project team of one pilot out of four was not able to participate in the test. Three user testing sessions were conducted with selected BIM models from the project of the remaining pilots. There were in total 9 users who are the project team members of the testing pilots. Some also took part in the interview and more details can be referred to Table 5. All testing sessions were conducted remotely.

Table 4. Interview and user testing participants

Participant	Interview	User Testing
Construction Manager	x	
CSE 1	x	
CSE 2		x
CSE 3	x	x
CSE 4	x	x
CSE 5	x	
Installation Manager	x	

Installation Supervisor 1	x	x
Installation Supervisor 2		x
Installation Supervisor 3	x	
Maintenance Manager	x	x
Project Engineer	x	
Project Manager 1	x	x
Project Manager 2		x
Project Manager 3		x
Project Manager 4	x	
Quality Control Engineer	x	
Field Support Engineer	x	

The multi-user VR environment

The VR environment of this study is built on DesignSpace – a multi-user virtual reality based design software. DesignSpace has been developed by 3DTalo, a Finnish start-up that offers Virtual and Augmented Reality solutions for business (https://3dtalo.fi/). All features established in the VR environment inherits from DesignSpace software with an addition of a new cabling tool. In the virtual environment, users can interact and communicate with each other through an avatar. Two navigation options are provided with teleporting allowing user to move instantly to a desired landing spot and flying to move freely without being attached to the floor level. Notable tools that are extensively utilised in this study for object manipulation are measurement tool to provide 1:1 measurement, drawing tool to draw 3D cube or freehand drawing, cabling tool to create representation of electrical conduits, and camera tool to capture the virtual scene.

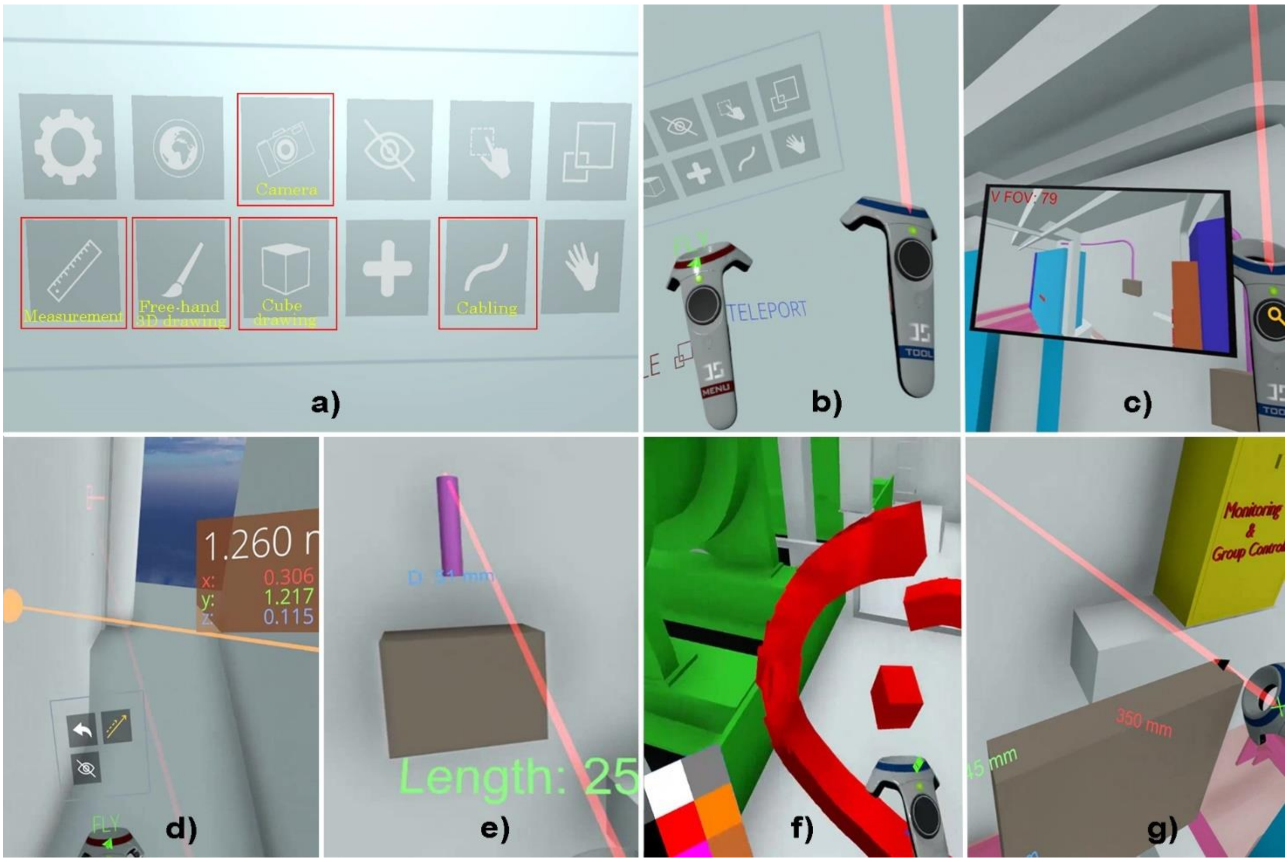

Figure 10. The VR environment: a) Menu with most frequent tools highlighted in red; b) Controllers with Navigation options (Teleport and Fly) on the left one; c) Camera tool; d) Measurement tool; e) Cabling tool; f) Free-hand 3D drawing tool; g) Cube drawing tool

Testing procedure

The testing session started with an onboarding section where each participant learns to use VR headset and the VR environment in 30 to 60 minutes based on their availability. Participants then performed given tasks within 20 - 30 minutes. To enhance collaboration, each task was divided into several sub-tasks so that participants must work together to complete it. There were two main task categories: machine room design review and machine room design planning. The former required users to examine the accessibility, maintenance aspects and installability of the machine room layout. Users then conducted a quick planning of by adding missing components and electrical conduit routing. Most importantly, participants have the freedom to propose and perform relevant tasks which are deemed beneficial for their work because the main objective is to let them experience using multi-user VR in the current machine room planning.

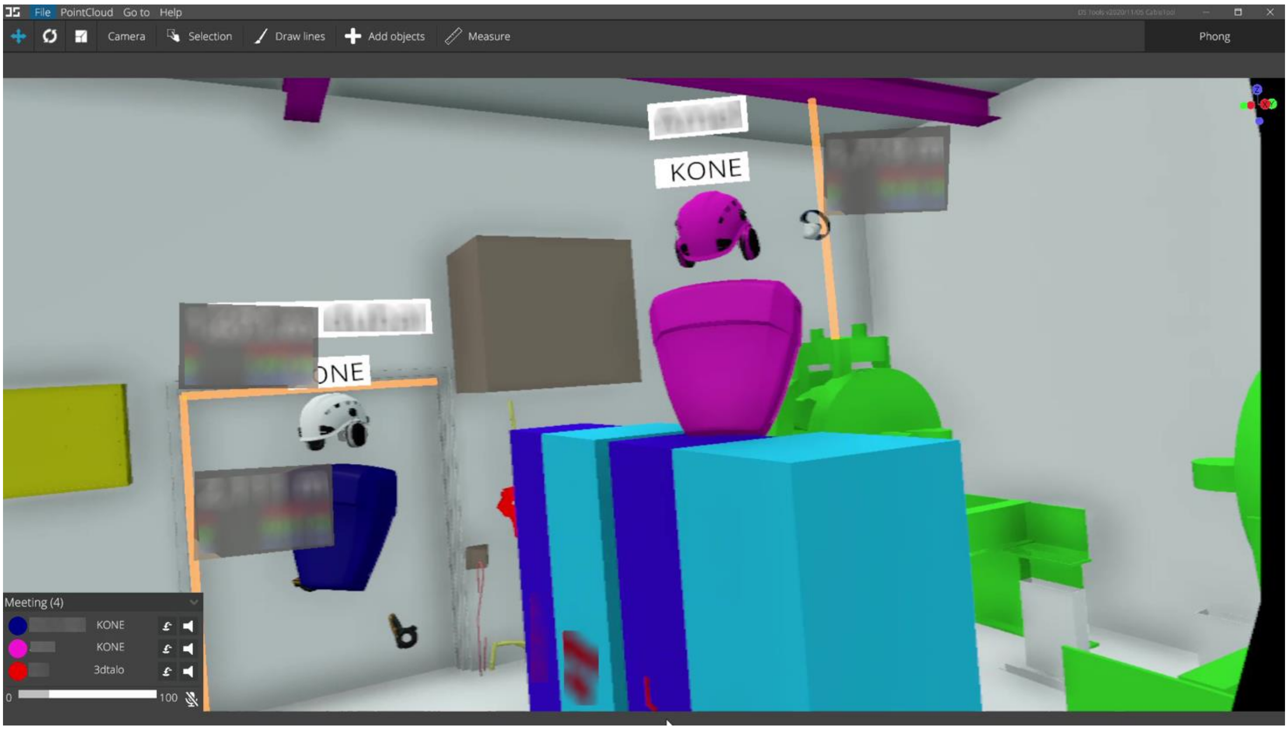

Figure 11. Users are performing given tasks in the multi-user VR environment during the test.

A semi-structured group interview was then conducted to collect feedback from the users about the tool in 45 – 60 minutes. The group interview serves as an open discussion for participants to reflect on their multi-user VR experience and connect it to their current workflow. Overall, users were asked to describe their experience using the VR environment and the benefits that they perceive in their current workflow. They were also asked which features were useful and what was missing and needed improving. Finally, the interviewer asked them to propose potential use cases and their perceived requirements and limitations to adopt multi-user VR in the current machine room planning.

After testing, a survey (Appendix) using Google Form was distributed to each participant via email. The survey aims to systematically collect their opinion for the use of VR in the current process from tendering to handover and quantitatively acquire their preferences on the features which have been implemented or need implementing in the future. A 5-point-system Likert scale on the level of agreement and priority suggested in Vagias (2006) was utilised. However, "It depends" was used instead of "Neither disagree nor agree" to improve clarity of the survey whenever respondent is in uncertain (Chyung et al., 2017). Even though this scale provides a neutral option as the evaluation of VR adoption depends on various factors, the middle point may offer a ground for respondent who do not put effort to answer. The issue was minimized by asking the respondent to justify their answer whenever they select the middle point. Moreover, the list of general use cases was adopted from Zaker & Coloma (2018) as they conduct similar experiment and provide a plausible use case list that fits the situation of AEC firms. The list of features was established based on the properties of the VR environment, the interview responses, and proposal from Wolfartsberger et al. (2018).

Testing preparation

Two testing criteria are set to maintain compliance with the scope of this study: multi-user VR and real-life task replication. A cross-country testing model (Figure 12) is established to ensure that there will always be two active users from two different countries at a time in VR. Each session utilised the project BIM-VR model from one pilot. Participants for every user testing were the project team members of the testing pilot and other KONE personnel from other pilots or the Global function located in Finland. The list of tasks conducted in the test was developed with the help of several professionals at KONE to resemble the actual machine room review and planning process.

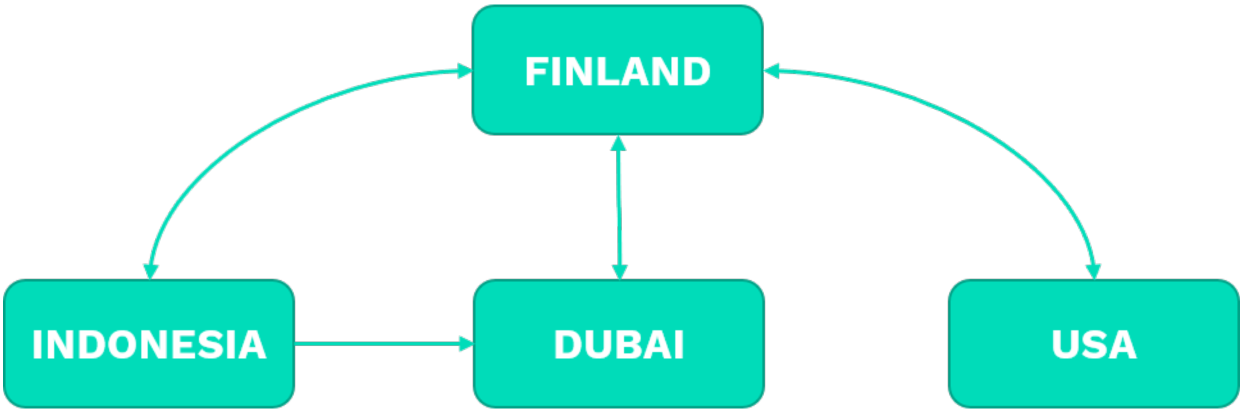

Figure 12. Cross-country testing model: Each user test involves users from two different countries.

The VR environment was modified with the aim to meeting requirement insights from the interview responses and literature review. BIM model was manually converted to the virtual environment with the help of 3DTalo because the automatic transfer from BIM to VR of the VR environment does not support the manipulation of the base model. In general, the conversion process started with creating a 3D model (.fbx format) from BIM authoring tool such as Revit (.ifc format) for the virtual environment via a game engine (Du et al., 2018; Zaker & Coloma, 2018). In this study, FBX 3D file format (.fbx) that contains elements' material, geometry, and relationship was exported from the BIM model in Revit (.ifc). The FBX 3D file was then modified in Blender to regain texture and adding label on critical objects such as drive cabinets because the default exporting function in Revit does not preserve model texture. The 3D file was then transformed into a virtual environment using game engine. Moreover, one of the CSEs participated in this study was consulted while building the cabling tool to ensure the strict compliance with KONE cable specifications and engineering requirements.

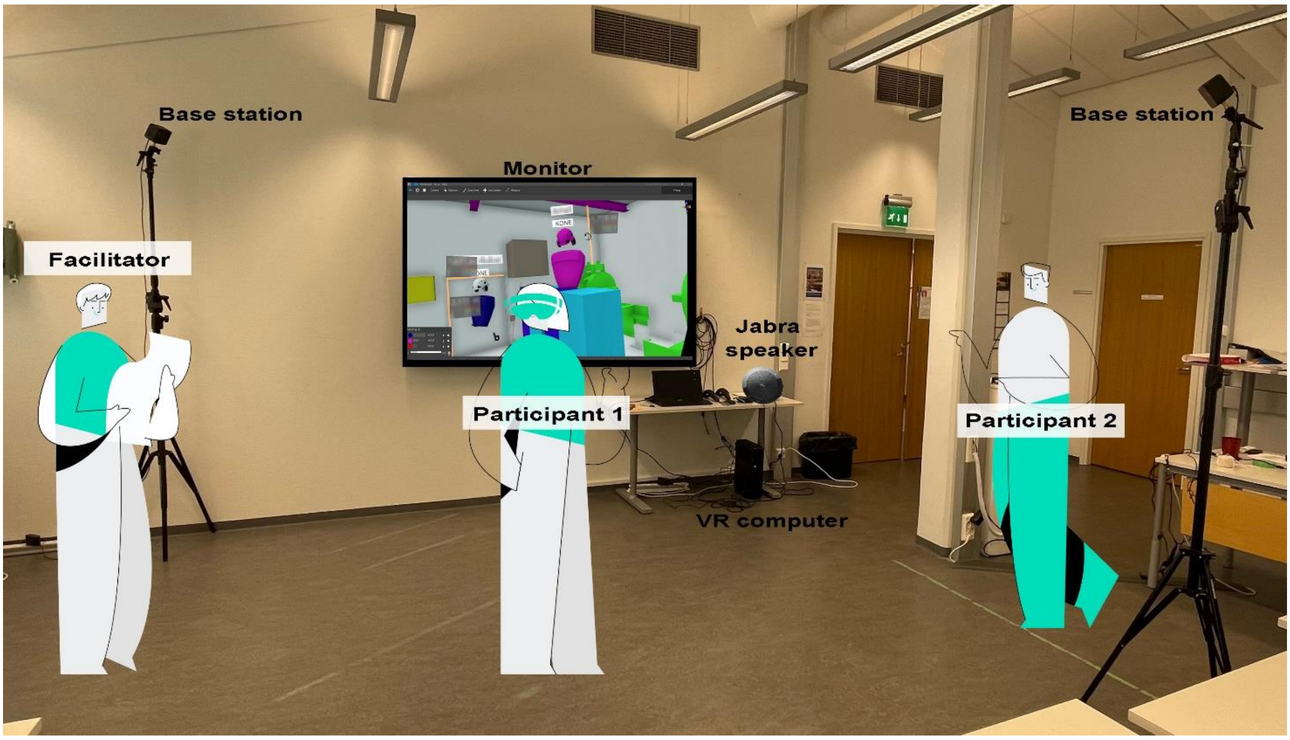

Figure 13. Physical set-up at each testing location.

In every testing session, two testing front lines were involved. There were also remote observers in each session. Each front line has one facilitator and two to three participants that take turn to use VR. Figure 13 depicts the physical set-up of each testing location. All communication between participants of the two testing locations and remote observers were conducted through Microsoft Teams. The VR environment allows users to communicate with each other; however, only active VR users can hear it. Therefore, this functionality was disabled, and Microsoft Teams was used so that remote observers can listen to what VR users are talking. In each location, a Jabra speaker was connected to the computer so that participants in the same location could hear and communicate to avoid echo. Figure 14 illustrate the virtual set up of Microsoft Teams. Each session utilised one BIM model from a pilot to create the virtual machine room. The VR view of the active VR user of that pilot was screen-shared. Besides, the physical view of all active users was shared for better observation.

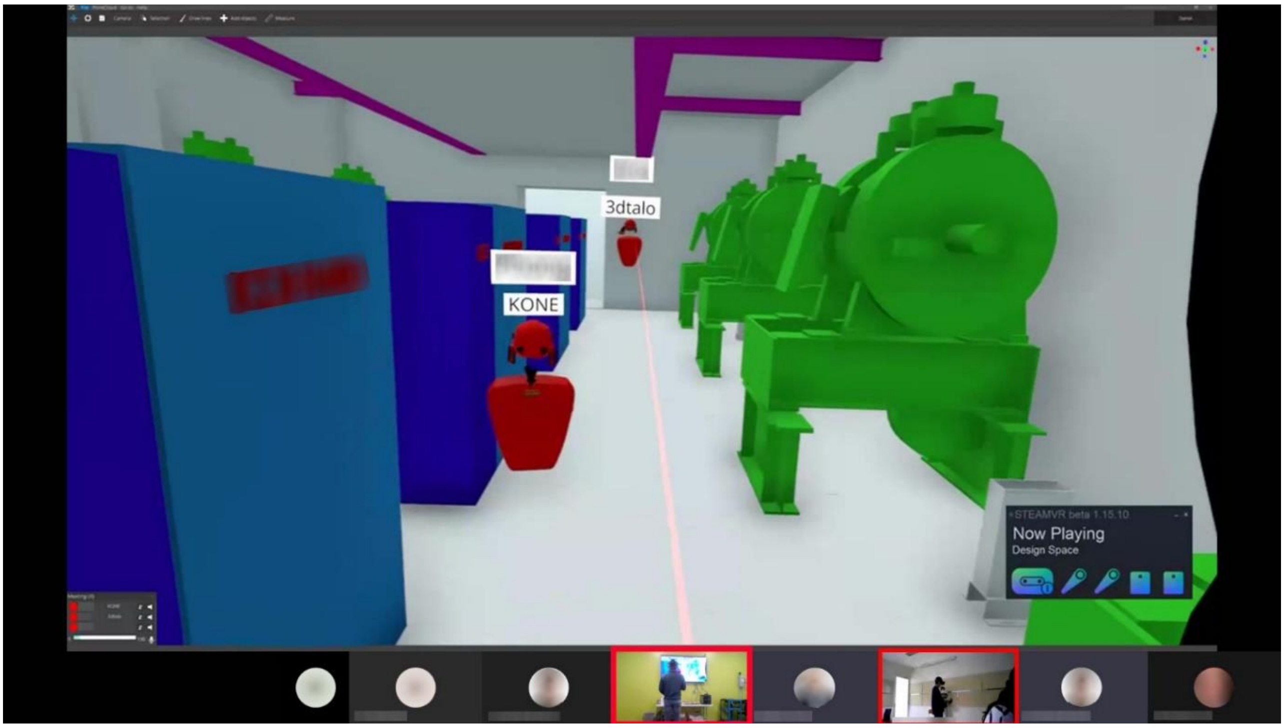

Figure 14. Screenshot of Microsoft Teams of the remote testing set-up. Main users' view of VR are screen-shared. Main users' camera was turned on (highlighted in red) for remote observation.

The VR headsets and computers used in this study are supplied by each front line. Details on the VR hardware are indicated in Table 6. Most importantly, all testing sessions were organised in accordance to COVID-19 safety regulation of each front line. To minimize the virus infection, all participants physically present in the testing area were required to wear a mask. Disposable protection masks were also required to be worn whenever using VR headset to avoid skin and foam contact. VR headsets were disinfected with alcohol wipe every time after being used before the next user.

Table 5. VR hardware used in user testing.

Testing session	VR headset	Computer system
1	Oculus Rift S	CPU Intel® Core™ i7-4720HQ @ 2., 8GB RAM, NVIDIA® GeForce® GTX 980M
	HTC Vive	CPU Intel® Core™ i7-8700K @ 3.70GHz, 32GB RAM, NVIDIA® GeForce® RTX 2080 Ti
2	HTC Vive Pro + Wireless adapter	CPU Intel® Core™ i7-8700K @ 3.70GHz, 32GB RAM, NVIDIA® GeForce® RTX 2080 Ti
	Oculus Rift S	CPU Intel® Core™ i7-10750H @ 2.6GHz, 16GB RAM, NVIDIA® GeForce® RTX 2070
3	HTC Vive Pro + Wireless adapter	CPU Intel® Core™ i7-8700K @ 3.70GHz, 32GB RAM, NVIDIA® GeForce® RTX 2080 Ti

	HP Reverb	CPU Intel® Core™ i7-8750H @ 2.2GHz, 16GB RAM, NVIDIA® Quadro P1000

3.3 Data analysis

All qualitative data obtained via individual interview before testing, group interview during user testing, and the author's observation of the user testing is analysed using affinity diagram method using Miro online whiteboard. Critical notes were written in the electronic post-it notes which are later clustered into groups to generate insights. Figure 15 illustrates an example of how a part of the interview response is analysed.

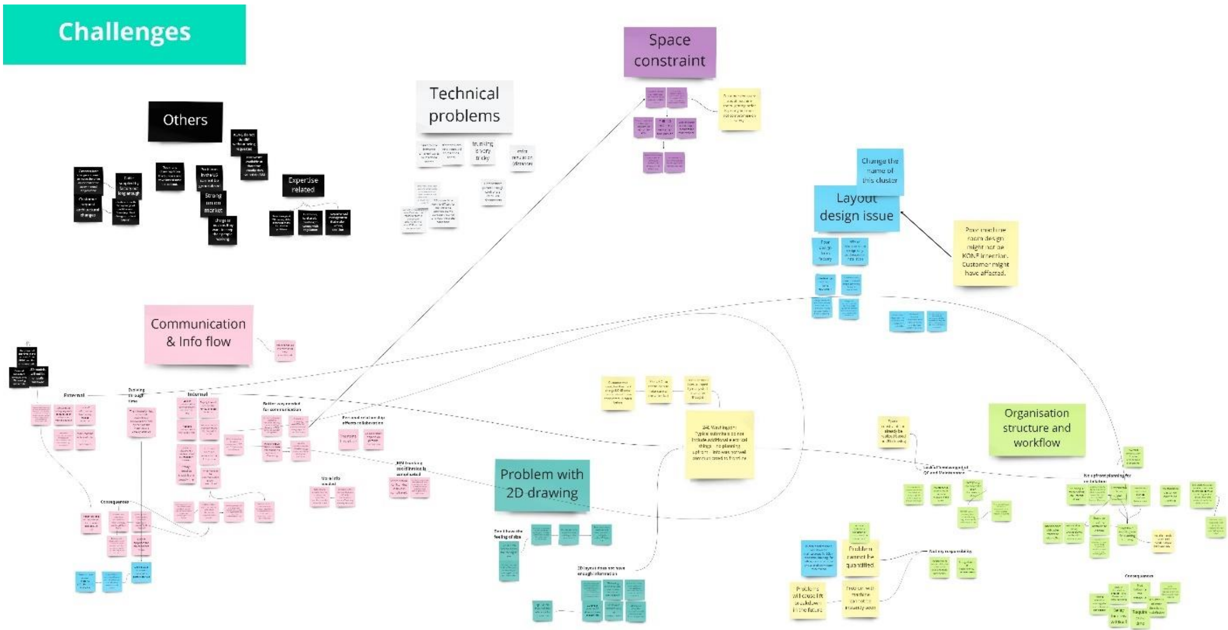

Figure 15. A part of the interview response analysis by affinity diagram on Miro.

The analysis is based on the objectives that have been determined for the interview and user testing. Moreover, due to the relatively small sample size (9 respondents), data collected in Question 2 and Question 3 in the survey are interpreted based on the graphical representation in the form of charts. Descriptive statistic is utilised to analyse the quantitative data collected from Question 8 on the priority ranking of the VR environment features in the Likert scale. Mean, mode, median, and standard deviation are computed using Excel. Interpretation of the result is based on all calculated parameters. This is due to the complicated nature of the response which is quantitative in the survey but qualitative in reality. Mean gives the overall evaluation while mode and median reflect on how the majority of respondents react to the feature. Standard deviation is used to determine the variation in respondents' opinions, which helps to indicate the uncertainty of the feature.

4 Results

This chapter presents empirical findings derived from the collected data. The chapter is dived into two sections. Section 4.1 indicates the responses from the interviewees before user testing while section 4.2 provides the results from the group interview and survey response of participants from the user testing as well as the author's observation during the test. It is important to note that findings in the first parts originate before the study participants are exposed to the use of the VR environment.

4.1 Interview response before user testing

The result from this section is divided into three sub-sections correlating to the pre-determined interview goal as discussed in Section 3.1. Section 4.1.1 describes the challenges that the project team members have been confronting in the life cycle of major machine room projects. Section 4.1.2 provides critical improvement suggestions from the interviewees and their wishes for a better workflow. Section 4.1.3 presents their perception towards VR and its use in high rise projects before exposing to the VR environment.

4.1.1 Challenges in machine room planning, installation, and maintenance

It is important to note that the challenges and consequences discussed in this section are from different projects and previous experience of the interviewees.

Technical challenges

The nature of an elevator machine room design is technically challenging. The elevator machine room normally has limited space for elevator machines and components as well as other equipment and building service systems. The positioning of the elevator company's equipment should be optimal so that other partners' equipment can be later placed without any interference. Besides, all equipment positioning must leave enough room for future maintenance activities. Furthermore, all components are connected by cables that run through electrical conduits. The design process requires precision in planning and installation due to the vast numbers of services to be linked and the cable's susceptibility to even a minor external physical or electromagnetic force, respectively. Similar to the cables themselves, the routing of the trunking was referred to as "the biggest concern" by all design engineers and installation supervisors. Determining suitable trunking routes for the varied types of cables while maintaining sufficient clearance for movement inside the room to avert safety risks (e.g. tripping) is demanding. The challenge is elevated significantly in cramped machine rooms as space is limited.

Complying with stringent codes and standards adds more complexity in the machine room planning. To meet the defined quality standard, KONE requires strict conformance to the company's engineering instructions in all machine room designs. The instructions derive from many layers of codes according to the local authorities and the KONE global company. These are extensive and detail all aspects of machine room design. For instance, adequate distancing, e.g. between machine and wall and clearance space in front of all components for future maintenance, must be achieved. Most importantly, the codes vary between different machine types and are subject to updates. Hence, designers and engineers must ensure the use of correct and up-to-date requirements for each machine type.

Figure 16. A 3D model of a 2-storey elevator machine room.

Interviewees also emphasised the complication of planning when 2-storey-machine-room is required (Figure 16). In this machine room, motors, drive and controller cabinets are in two different levels. According to the code, the maintenance technician must be able to observe the motor movement, which is controlled from the cabinets on the upper floor. One solution is to have a steel grating floor instead of concrete, allowing a line of sight between the controller and motor. However, the technician might drop small parts or tools to the motors below, causing severe damage and safety risk. CCTV is another solution for observing the motor movement. Nevertheless, the view angle is limited, and motor monitoring via CCTV is therefore ineffective. Having equipment on different elevations also introduces more technical difficulties in cable and trunking planning and installation.

Issues of the 2D drawing

All interviewees addressed the lack of "feeling of size and space" when using 2D drawing. There is a tendency to under-estimate the size of the equipment. "It was hard to imagine when seeing it on the drawing only. I once thought a 6m cube was not so big but then shocked when saw it in real life", said CSE 4. This issue causes inefficiency in the installation since additional planning and possible rework is required. One of the managers experienced the miscalculation of the equipment size from the main contractor even though there was a face-to-face discussion on site. He said that trunking had to be rerouted because the equipment took more headspace than expected. Furthermore, spatial comprehension from a 2D drawing is limited and often deemed incorrect as expressed by all Project Managers, Installation supervisors and CSEs. People usually underestimate how small or cramped the machine room is in reality, leading to challenges in logistics and executing the installation on site. Regarding the same project mentioned in this paragraph, an extra 8-9 weeks was required to install all machine room units due to this issue.

2D drawings are referred to as “too simple”, and that they do not contain enough information. The standard drawings from the supply line engineering only contain the main components, and the cable routing and trunking are not included. “Typical submittals do not include other trades’ equipment or additional components that require special attention”, said one of the managers. One of the engineers stated that “it is hard to inspect thoroughly because the drawing that quality control receive is not detailed enough”. Together with communication and upfront planning issues (later discussed in this section), one project’s machine room was unexpectedly packed with additional components as “an afterthought”. This problem resulted in several tens of thousands of euros extra cost for the electricians to adjust all electrical conduits in the room.

Space constraint

Space constraints are a major problem and experienced in 30% of high-rise projects. As the amount of elevator equipment required remains the same, smaller machine rooms create more engineering difficulties, and most importantly, challenges for future maintenance. With insufficient space reserved, access to the machine room and other maintenance tasks such as machine replacement or repairing is limited. Hence, this situation elevates safety risks to future maintenance technicians.

The elevator machine room size is specified by the customer’s architect together with the elevator consultant and structural engineer. Both Installation Manager and Project Manager 4 indicated that customers tend to keep the machine room as small as possible. In high-rise projects, machine room space is not rentable, hence generating no profit. The customer’s architects also might not be aware of the future challenges in maintenance or prioritize them, even if warned. One of the managers indicated that competitors might agree with smaller machine room size in response, to gain favour during the sales phase, even though this involves increased risks to future technicians.

Machine room design issue

Most machine room designs only address the functioning of the elevator and installation process, with 95% not being optimised for future maintenance activities. Frequent issues that are encountered are insufficient clearance space in front of cabinets for maintenance work, as well as between motors and wall for dismantling or transporting if needed. Another design issue is the interference among the elevator company’s equipment and with those of other partners. Installation supervisor 3 reported a case where trunking routing cannot be conducted due to a clash with a machine beam. Most importantly, the problem was only realised after all equipment was installed, hence requiring extra time to resolve the issue.

Nevertheless, it is essential to emphasise that the issue might not be the company's intention but caused by the client's requirements.

The flow of information, communication and collaboration

CSE 4 indicated that the current flow of information with external stakeholders is complicated and inefficient. One of the engineers revealed that critical information (e.g. other trade's equipment in the machine room) is often missing, not supplied by the customer in time, or occasionally incorrect. This delay in information sharing leads to the elevator project team's inability to start planning, e.g. trunking routing, early enough. The many layers of approval within the company and with the customer account for the current issue. For instance, machine room drawings must be approved by different consultants from the customer and main contractor before the installation process. Project Manager 1 reported a case where the field construction team of the Main Contractor almost drilled a wrong hole in the building for the elevator. This incident results from the incorrect drawing given by the main contractor to the construction team. It could have been a costly mistake but was prevented in time. However, there was a 1-week-delay to get everything back on track.

Within construction industry the communication and collaboration between the supply-line and front-line has scope for improvement. The current communication between supply-line and front-line is need-based. In other words, it takes place only when challenges occur. It needs improvement because the supply-line decide on the type and positioning of all equipment while the front-line coordinates every adjustment with the client. Moreover, the specific information that is required by different stakeholders and when to communicate is not clearly identified, documented and trained. One of the managers indicated that every project in his frontline unit would need to install at least one additional switch after all equipment was installed. Structural changes such as modifying of walls to bringing the electrical circuit for the missing components might be required. The field team expected the supply-line to provide details of all switches to be installed. However, supply-line argues that the field team must be responsible for figuring out the information. Another incident regarding this communication issue was reported by Project Manager 3. The supply-line did not communicate the installation of a minor component to the front-line, which is estimated to cost several tens of thousands of euros for extra materials and installation labour in response.

Other communication and collaboration challenges were also identified. Firstly, CSE 4 indicated that the detail of information evolves significantly through time. By the time materials need ordering, crucial information is likely to be missing. The quantity of materials will, therefore, be estimated based on general standards that are not tailored to each machine room. This situation results in 20 - 25% of excess materials as reported by one of the engineers. Secondly, personal relationship affects collaboration. "The name has a face", said CSE 4. Knowing the person essentially accelerates the response time and fosters collaboration. Hence, the current virtual setup, e.g. teleconferencing without face and interaction, is not ideal for collaboration. Thirdly, the current means of communication is not effective. The CSE 3 reported the difficulties to illustrate to external contractors that they could not place any equipment in particular areas due to potential clash. A Maintenance Manager also expressed the challenge to discuss with clients the safety risk and limitation of future maintenance due to space constraints. Moreover, installers use 2D drawing as the reference onsite with little information or access to the 3D model. The Installation supervisor 3 suggested implementing alternative visualisation approaches so that they can understand the on-site installation logistics better. Finally, trunking routing coordination using BIM is demanding. The CSEs will initiate the drawing in BIM and transfer the model to the field team for comments. Adjustments proposed by the latter will then be executed by the former, making the process time-consuming.

Organisation and workflow structure

The Maintenance Manager and Quality Control Engineer stated there was a lack of maintenance and quality control involvement in the current machine room planning. The communication between others with maintenance and quality control responsibilities remains limited to none. In some areas, the quality control process only occurs in the last stage of the equipment delivery. The Quality Control Engineer remarked, “they do not really have any final say since everything is built already”. The quality control process is also limited to using a simple 2D drawing as a reference. Hence, the final inspection is not thorough.

Currently, before the equipment arrives in the machine room, the process does not include detailed planning of the cable routing and trunking. Primarily, the running of the trunking is conducted “on the fly” and field fit. Since the installation team must plan trunking routing before the installation, Installation Supervisor 1 indicated the risk of not having sufficient time for adequate planning. The field team often encountered unforeseen interference between the elevator company’s and other stakeholders’ equipment, causing installation delay or rework. The additional labour to be recruited due to poor planning is needed to maintain a timely delivery, which increases the cost while reducing profit. Moreover, the dependency on on-site coordination is significant in the current process. With no standard trunking design on the layout drawings, each installer has a different approach, and they often do not read the general installation instructions. Thus, there has been inconsistency in trunking and overall installation quality. Lastly, inefficient site logistics is another issue. Installation Supervisor 1 indicated several consequential challenges such as imprecise material delivery, incorrect installation with the need to dis- and re-assemble components, untidy installation scene, etc.

The strong division between teams, though beneficial for management, challenges the collaboration and workflow coordination within the construction industry One of the managers indicated that each team has their own area of responsibility, and the challenges faced by others in the process might not concern them. One of the engineers indicated that all consequences occurring after the hand-over stage would be directed to the maintenance team budget. The impacts of incorrect machine room design and installation can be neither recognised immediately nor systematically quantified. The expense for the installation department to resolve future problems can be estimated. However, time and effort, which is cost in reality, for obtaining permission from the builder and planning to address disruption for the building users are unquantifiable. Therefore, there is a need for a well-coordinated work- and feedback-flow between teams to enhance the quality of project delivery.

Other challenges

Unexpected layout changes from customers in equipment positioning and building structure may affect the progress of machine room planning. Extra time is required for re-planning to avoid interference between the equipment and to find other suitable materials (e.g. longer cable) for installation. Besides, CSE 4 expressed that it is incredibly time-consuming to modify and mark up suitable drawings sent by the builders for the supply-line in the initial stage. Another issue is the limited availability of BIM competent persons and systems in the different regions and front line engineering departments. Conducting BIM depends on the client's request, and its cost might not be covered during the sales phase of the project. This situation implies that the BIM implementation expenses will be then from the project team. Moreover, A Field Support Engineer commented that the lack of construction competency, especially in the elevator equipment, occurring both internally and externally will have a notable impact. First-time personnel of any kind in the roles such as engineer or even manager might struggle to plan trunking routes that comply with the complex regulations as well as make informed decisions in project coordination.

4.1.2 Improvement suggestions and wishes

Most interviewees suggested having more upfront planning for installation would be beneficial, and the wiring and trunking routing should be conducted before construction. It assists the team in foreseeing and resolving potential interferences of all equipment. A coherent plan for site logistics is indispensable and should also be carried out, with the aim to provide more guidance for the installer, enhance material delivery efficiency and avoid reworks.

Collaboration between the supply-line and front-line, including maintenance and quality control, should be enhanced. More coordination sessions to examine the machine room layout is suggested. Consideration for future maintenance and modernisation should be raised and reiterated throughout the project. Project Manager 3 advocated the design for maintainability approach at the initial design stage. Overall, the goal is to produce a highly accurate and detailed machine room layout design.

Obtaining early or timely information of all stakeholders' equipment that would be placed in the machine rooms was also suggested. CSE 4 underscored the need for knowing the size and installation method of such equipment to compliment the site logistic planning. Furthermore, Project Manager 1 hoped to find a way to construct the project's first machine room for reviewing without rushing. Improvement can then be determined before continuing with the others.

4.1.3 Perception of VR before user testing

All interviewees had no or little experience with using VR. Those with no experience has seen VR via some demonstration and social media. Others have tried standalone VR headset without controllers through commercial demonstration in shopping malls. None of the interviewees has used VR in their work nor perceived it as a collaboration tool. However, now everyone is aware of what VR is and how it works.

Positive response

The perception of VR usage in general and at the workplace is positive. VR is deemed beneficial by all the interviewees. Installation Supervisor 1 believed that the implementation of VR would improve the current workflow and make it more efficient. "VR could provide insights that are hard to replicate", said Project Engineer. VR is seen to be a useful simulation tool for design in machine room planning, installation and maintenance. The high realism in spatial comprehension is the crucial feature, accounting for the well-received VR application. CSE 4 and Maintenance Manager expressed that VR might help them "feel the real size" and realise space constraint issues.

Potential use cases

Firstly, most interviewees stated that the VR should be utilised in installation planning and training. By visualising the machine room before installation, Construction Manager remarked on the ability to foresee all the logistics required. Installation Supervisor 1, CSE 3 and Project Engineer commented that it would aid fitters to see the installation process better, hence minimising the safety risks. Secondly, VR can be used as a means of communication for coordination meetings between stakeholders internally (teams) and externally (customers). Users can demonstrate their points visually, which attracts more attention from the participants and perhaps becomes a catalyst for conversation.

Thirdly, interviewees suggested that VR will come in useful for design planning and review. During this process, there might involve repositioning of equipment, the adjustment of one cabinet possibly requires a similar correction with others, which is often overlooked. This issue is expected to be minimised in VR because it offers reality-based object manipulation. The required follow-up adjustment is thus more noticeable. Interestingly, CSE 4 imagined that time spent on fixing a problem in VR could be translated into the time required to do so in reality (e.g. 1 hour in VR is equivalent to 10 hours in reality).

On the other hand, interviewees also indicated impractical use cases of VR for maintenance, quality control and supply teams. Maintenance Manager expressed the concern since "they do not have the final say" in machine room planning. This issue coincides with the Quality Control Engineer's response summarised in Section 4.1.1. Even though the Project Engineer considers VR as beneficial, the added benefit is not significant enough to introduce VR into the supply-line. Their focus is on creating 2D drawings with positioning components, which is well-defined and needs to comply with the codes and standards.

Features requested in VR

Most of the requested features were driven by the proposed use cases. In both installation and design where planning involves a high level of object manipulation, the interviewees requested to be capable of moving the equipment model part by part in VR. Realistic movement should also be well-simulated in VR. CSE 3 and CSE 4 suggested real movement of cabinet doors such as sliding or opening. Besides, CSE 4 indicated the need for an effective note-taking option. Tagging people is also requested, which signifies to the person in concern about the adjustment made in the model. Most importantly, interviewees proposed that all information on equipment in the machine room should be included in the simulation. This request would not just be limited to the name but also addresses other properties such as object dimension and material type.

Requirements and perceived limitations of VR

The complex hardware required to implement VR is one of its limitations. Interviewees expressed their concern on the cost and the amount of space needed to facilitate a VR system. The construction site environment is another factor that might not be suitable for storing and using VR. The computer systems and the headsets would be damaged due to the presence of dust. The internet connection at the site is also sometimes not existent or unstable. Therefore, CSE 3 perceived that 2D-drawing on paper is more ergonomic than VR in this case. CSE 3 also deduced that AR is perhaps more suited to be used on-site than VR.

BIM is indispensable and becoming mandatory for creating the virtual environment in construction, which requires substantial resources to carry out. There is currently no automatic process to convert a 2D layout (.dwg file) to BIM. Manual transferring takes time, especially when there are no BIM-capable personnel in the project team. In such a case, the process is directed to the supply-line engineering or hiring a skilled user. Creating a BIM design by the supply line team for a simplified machine room layout containing six cars without trunking requires 24 working hours and two weeks lead time.

The quality of the planning outcome in VR is highly dependent on the quality of BIM construct. CSE 4 emphasised that high accuracy is crucial when transferring 2D layout to BIM. To achieve this, Field Support Engineer indicated the need to involve competent personnel from both CSE and installation teams. In this context, Project Engineer remarked on the need for coherent knowledge transfer between the two teams. The installation team has the field expertise and experience to know the actual need when designing machine rooms. Hence, it is essential to direct that knowledge so the CSE can accurately conduct BIM. Besides, it is also critical for the CSE to communicate the design details with the installers effectively. They can thus utilise the information and make informed decisions on the construction site.

Both Field Support Engineer and Project Manager 1 indicated that successful VR implementation could only be achieved when sufficient resources are available. Resources here refer to budget, time, and effort. They believe that VR is currently not plug-and-play, hence requiring substantial training for users to utilise the technology effectively. Since different stakeholders in the company has different schedule intensity, it is important to communicate in advance and provide suitable training sessions.

Other concerns regarding the use of VR in planning and collaboration

Project Manager 1 and CSE 5 prefers room-scale VR rather than seated VR. As they anticipate experiencing the realism of VR, being able to function naturally like in reality, e.g. walking around, is crucial. They are also afraid that the difference between moving around in VR and being static in reality will cause headaches.

Furthermore, one of the CSEs is concerned whether the benefits that VR brings to the machine room planning process is significant, compared to showing the 3D BIM model on a 2D screen. Implementing VR is introducing an extra step to the process, which requires substantial investment. Even though the installation process is well-planned by using VR, Field Support Engineer noted that an experienced person in charge is still needed onsite to eliminate any wrongdoing. Hence, the added value should justify the future resources allocated.

Moreover, Project Manager 1 addressed the challenging consequences of showing VR to the customer. There is a need to understand the client's level of competency in BIM execution and VR, hence inferring if this is beneficial or not for the customer. They might also set a higher expectation after seeing the machine room in VR, which in return creates more challenges for the project team.

Lastly, CSE 3 indicated that the acceptance of applying VR in the workflow or as a platform for collaboration is not guaranteed. Some people are reluctant to the technological shift because it might disrupt their workflow. Therefore, the purpose and value of VR should be communicated well to all potential users.

4.2 User testing: observation, group interview, and survey responses

This section is divided into four sub-sections corresponding to the pre-determined objectives of the user testing in section 3.2. The first section (4.2.1) describes both positive and challenging experience while conducting the user testing. The remaining explain how participants perceive the benefits (section 4.2.2), requirements (section 4.2.3) and the application (section 4.2.4) of VR and specifically the VR environment in the their current workflow.

4.2.1 User experience: advantages and challenges

Positive responses toward the use of VR were received during three user testing sessions. Some challenges have been found during the testing phases, which might affect the overall user experience with the VR environment.

VR brings collaboration to life more effectively

Participants were captivated by the experience of planning and reviewing machine room design using VR. They remarked on the greater interactivity of viewing the machine room in VR than presenting it in BIM on a 2D screen. They also decided to spend up to one more hour in the first testing session and other onboarding sessions to explore VR. Besides, participants in the final testing asked for more access to VR for their local front-line. Project Manager 2 indicated the desire to have another machine room with some design challenges imported in the session to perform design review. The manager also remarked that other project managers in the same region would be willing to investigate such use of VR.

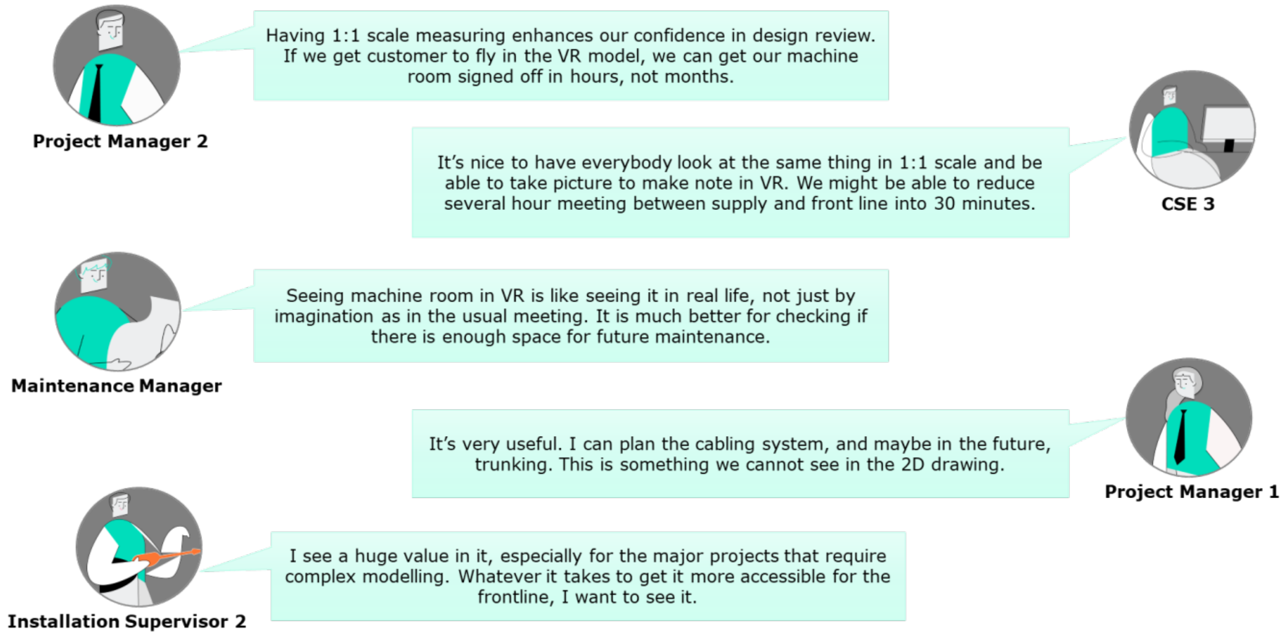

Figure 17. Participants feedback on the VR collaborative environment after user testing.

A high level of immersion was observed during the sessions. Participants in the first user testing indicated being in the same space even though they are located in different countries. All participants tend to use both verbal and non-verbal expressions as in face-to-face discussion. Verbal clauses such as “I lost you”, “where he is standing”, “can you stay behind me”, etc. and deictic expressions like “here” and “there” were used. Some participants also utilised their hand gestures to address positioning. One of them tried to poke another user because the other was blocking his way. CSE 2 and Maintenance Manager indicated the feeling of standing in the installation site. CSE 3 and Project Manager 4 attempted to sit on the floor to view beneath the machine. Furthermore, all indicated the collaboration conducted through VR is valuable and superior to Microsoft Teams which is the current means of communication for remote working. CSE 4 depicted VR as “an advanced video call” but “much more interactive”.

The participants also realised an excellent sense of realism. They all remarked a high level of dimension and spatial comprehension referred to as “true size”. This benefit was brought by the ability to view models in 1:1 scale, which is deemed the most critical VR property by all participants. Additionally, the overall layout of the machine room is better comprehended through the real-scale-visualisation. Design adjustments and modifications are easily communicated using VR. The Maintenance Manager noted that the team usually has to imagine those changes in the conventional meeting, increasing the chance for design errors. Installation Supervisor 2 indicated that VR could offer tremendous value to the machine room planning and installation process, especially for major projects. With interactive object manipulation, the real-scale visualisation in VR potentially helps the project team make more informed decisions.

Figure 18. Two users are reviewing the machine room layout design in the VR environment.

Some features in the VR environment are frequently utilised and deemed significantly useful in the testing sessions. The measuring tool is highly used and appreciated by all participants. Project Manager 2 indicated that the tool is crucial because it allows users to check if the equipment is installed correctly by accurate real-scale measurement. Additionally, Free-hand drawing will enable users to quickly markdown or highlight changes made to communicate with others easily. Drawing cube helps users create boxes to represent missing components such as drive cabinets or main switches. The Cabling tool allows users to plan electrical wire before installation following engineering standards, making the process simple while complying with the strict codes. Moreover, the Camera tool enables participants to efficiently transfer changes made in the session visually to others by capturing the virtual scene.

Practical challenges during the user testing

Health and comfort issues were experienced during the testing sessions. Headaches were reported in the first and second user testing with two (out of four) and one (out of three) cases, respectively. It is important to note that one case from both sessions is from the same participant. That participant (female) experienced sustained headaches after every 7 - 10 minutes of VR exposure while the other participant (male) reported once after 30 minutes using VR and fully recovered after 5 minutes of resting. No health issue was found in the third testing. All participants in the first session indicated a high level of brightness in Oculus Rift S and HTC Vive headsets, accounting for the reported health issue. Another cause could be from the IPD non-fit with the Oculus Rift S, as discussed in Section 2.5. Participants in the third testing reported that the VR headset kept slipping away from their head regarding the comfort issue. The protection mask used in the session is suspected of causing the problem as it might reduce friction between the mask and the headset.

The nature of the VR environment also caused some challenges. The virtual environment does not have clash detection. As the cube created by users and the wall share the default texture, some participants were not aware that parts of the cube were submerged in the wall while moving. This condition lead to error in measuring as the participants return to check on the cube size. Moreover, severe synchronisation issues in the first testing disrupted in and prolonged the testing procedure. There were differences in what participants in two front-line units saw in the virtual environment. The action done in one country was synced with enormous latency or even not synced. As a result, the virtual scene was a mess-up (Figure 19), and collaboration could not be facilitated. The issue was resolved by restarting the program, but a synchronisation delay persisted. Unstable internet connection was suspected as the leading cause for this challenge.

Figure 19. The mess-up VR scene due to synchronization issue in the first user testing.

Participants also noted some usability challenges with the VR environment. Firstly, even though onboarding sessions are given, they could not remember where and how to use the tools. Secondly, participants tend to look at their eye level when performing drawing while the drawing process is initiated on the right controller. Hence, they were always confused because they did not see what they were trying to do. Thirdly, some tools are not intuitive and difficult to perform. Participants complained that objects were not highlighted when being chosen in the Hide Object tool. The tool requires users to slightly press the trigger to highlight the selected object before firmly pressing the trigger to hide it. In addition, they noted that the "snap-to-surface" feature of the cabling tool is complicated. Drawn cables by default are attached to the surface; hence, users need to disable that feature to freely draw it in the air and reselect to snap the wires back to the intended surface. Moreover, the way that the Moving tool utilises the controller is deemed "not convenient". In the VR environment, moving objects is done via the touch wheel while copying objects is conducted through the trigger. However, participants emphasised that the trigger is more intuitive to press. They kept pressing the trigger to move the object, making them need to hide the object and perform the action again.

Some challenges also occur with the implementation of remote user testing. In the first session, there was a language barrier with one participant, making the communication complicated. Latency in transmitting voice audio in Microsoft Teams also contributed to the added complexity in communication. There was also no facilitator helping from the other country. Hence, the author had to facilitate participants across two countries simultaneously. Together with synchronisation issues and complex communication, the facilitation was challenging. In the second testing, the voice of the person wearing the VR headset was challenging to hear by others remotely. The play area was far away from the Jabra speaker's microphone, making recording the user voice difficult. The session also took place in an open space, which diffused the user's voice and contributed to the issue. Moreover, participants indicated the problem with referencing to a particular engineering requirement and drawing details. Both Project Manager 1 and Installation Supervisor 2 noted that they could access the engineering instruction and the 2D drawing whenever needed in design review sessions. However, they were not able to do so while wearing the VR headset.

4.2.2 The benefits of multi-user VR

The overall benefits of applying multi-user VR in the machine room planning, installation and maintenance process that are reported by the participants are illustrated in Figure 20. Essentially, the three main advantages, visualising with real scale and high immersion, ease of communication, and freedom of viewing create the foundation for others. Consequently, VR provides a more intuitive environment for planning that helps the project team easily identify potential constraints and challenges in the installation and maintenance process. Adding the multi-user aspect facilitates collaboration not only within a team but also with other teams in the company. Overall, using multi-user VR enhances the project team's confidence in design review while saving its cost and time. Ultimately, these benefits foster KONE's brand as an innovation-driven company.

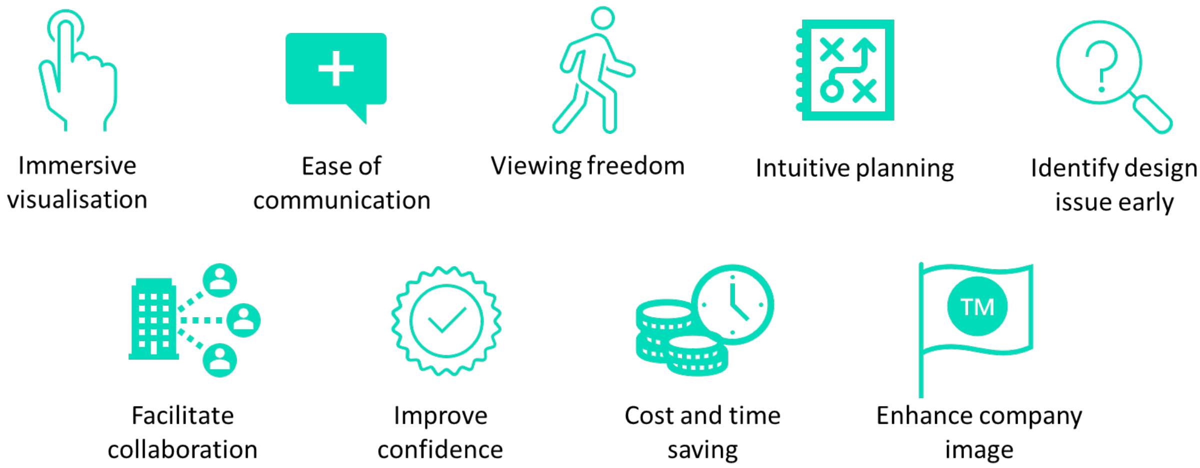

Figure 20. Benefit of VR found by the participants in user testing.

VR enables an immersive perception of the machine room layout with 1:1 scale. Seeing things is always better than only imagining as emphasised by Maintenance Manager and CSE 2. Participants also recognised the difference in size between seeing the layout in 2D drawing or BIM and VR, which helps the team make informed adjustments. Project Manager 4 said the machine room "looks smaller than I imagine" and proposed to "move the controller a bit to the centre so we will have more space for people to get into the machine from behind the controller". CSE 4 also had a similar experience when realising that the main switch was bigger than expected.

Multi-user VR reduces the friction in communication between users. Participants were able to use and take advantage of both verbal and non-verbal expressions. By combining those, such as pointing at a component (hand gesture) and verbally explaining the user's intention, others can easily understand the message. Besides, CSE 3 expressed that "having everybody look at the same thing" even when you are in different locations simplify the communication process. Project Manager 1 also added that VR captured the other's full attention compared to the conventional online meeting, accelerating the message delivery in communication.

VR offers users a freedom of movement to view the design layout without being restricted to certain viewpoints. CSE 4 indicated that only either a section or elevation of the layout could be viewed via 2D drawing at a time. The engineer noted that having the freedom for viewing comes in useful, especially when there are irregularly shaped objects. Project Manager 1 appreciated the total control to move around and look at any direction in VR. Communicating BIM currently involves showing on a flat screen, meaning that others need to ask whoever presenting to adjust the view accordingly.

VR was deemed as more intuitive for machine room planning by all participants. Project Manager 1, Installation Supervisor 1, and Installation Supervisor 2 indicated VR makes wiring, trunking, site logistic and future maintenance planning easier. During the testing, CSE 3 was able to draw a cable that he has been trying but not yet managed in Revit. The engineer expressed "much easier to spin the model (view) around to see it from different angles" because performing similar tasks in Revit requires complex tool manipulations.

The virtual environment helps participants easily identify potential constraints and challenges onsite. In the first user testing, Project Manager 4 found one minor issue that would cause future disturbance for the installation and maintenance team. The manager also noted that they might have space constraint issues if equipment from other stakeholders is later installed. During the second testing, a challenge for future wiring of the current machine room layout was recognised. The participants hence utilised the session to reorganise some components quickly. Moreover, a main switch was added to the layout during the session. The Maintenance Manager quickly spotted an interference with the main switch for the machine's future movement because there is not enough clearance space. Similar findings were also found in the final testing session.

Collaboration between participants was easily facilitated, thanks to the multi-user VR environment. This benefit primarily originates from the ease of communication explained earlier in this chapter. Project Manager 1 indicated that collaborative VR is most useful when making arrangements for the equipment. In the final testing session, CSE 3 utilised the time to demonstrate and validate the cable he needs to plan with his manager. The engineer found it "much easier than showing this in Revit" and took much less time than he expected.

Being able to measure and perceive the machine room layout accurately helps improve the confidence in design review. Project Manager 2 and Installation Supervisor 2 remarked with great satisfaction that the model they design has enough space for maintenance and putting electrical conduit behind the motors. Most importantly, having the VR layout can serve as measurement proof to communicate with the installation team. The extra confidence gained in design review helps gain control over site logistic planning. Project Manager 4 noted that the installation team would take over the decision-making process if there is any ambiguity, which is often not fully optimised for labour and cost-saving.

Overall, applying multi-user VR can help the project team save time and costs. Coordination meetings between supply-line and front-line teams can be shortened to one 30-minute-meeting, replacing the need for 2-3 longer sessions. Project Manager 1 indicated that real-scale measurement in VR provides a more accurate estimation of materials. This benefit hence leads to the reduction of excess amount and expenses of materials. Moreover, Project Manager 4 indicated that having clients using VR to collaboratively review machine room design can "get our machine room signed off in hours, not months". Getting the clients to approve machine room layout is a critical step and could be a roadblock if prolonged in machine room planning and installation. By using multi-user VR, every adjustment can be immediately demonstrated and assessed by the client, potentially reducing the time spent of the current process of design approval from months to just hours.

Ultimately, the application of VR can reinforce KONE brand as the leader in technological advancement. Project Manager 4 remarked on the story of how he has used 4D BIM in the past project. The 4D BIM was utilised to create a video demonstrating how KONE would install a challenging component to the main contractor. It has left a powerful impression on the main contractor, who later asked other companies to provide such a demonstration. Hence, implementing VR could strengthen KONE's image in the industry, enhancing its market competitiveness and attracting more clients.

4.2.3 Requirements to apply VR in machine room planning

Participants have raised many requirements that is critical to the successful adoption of VR in the current workflow. High accuracy in the 3D model, effective onboarding and robust implementation, as well as suggestions for new features of the VR environment are found.

The need for more accurate models

The machine room model dimension in VR must be as accurate as possible to the actual machine room. As planning is entirely based on 1:1 scale measurement, significant deviations can severely impact future installation. Besides, CSE 4 noted that some components like drive and controller cabinets exist as one single unit. Such components should be grouped when conducting BIM. Hence, they can be moved together to simulate realistic movement.

The machine room model in VR should also include all physical components. CSE 2 elaborated on the requirement to include all equipment, building structure, and the mechanical, electrical and plumbing (MEP) system. This request is highly recommended for the internal design review. Like in this study testing, having only elevator equipment might underestimate the machine room's complexity and cause users to overlook potential interference. CSE 3 and Project Manager 2 pointed out that achieving the requirement depends on the client's BIM progress. They also noted that communication between the company and clients plays a vital role in acquiring the full model.

More details on some objects are needed in the future. For instance, drive and controller cabinets are currently depicted as boxes. Details such as cabinet doors and minor components inside should be illustrated in VR. CSE 2 indicated that customers nowadays expect a higher sense of realism in a 3D model demonstration. As a result, more collaboration with the Research and Development department is needed to ensure each part's BIM availability whenever new equipment is developed.

Effective onboarding process

VR onboarding or training materials should be tailored to different needs. There were significant distinctions in VR competency between different people despite having similar time spent on learning. The CSE, experienced in conducting BIM, learnt to use VR faster and remembered how to use it longer than others. Hence, training materials should be designed to cater to different levels of technological competency. VR training should also be case-oriented to help users learn particular tricks to perform high-level tasks. Moreover, quick guide for using VR should be considered. Such materials specifically aim at those familiar with VR but have not used it for a long time.

VR training for users should be conducted frequently. All participants argued that having more training in terms of time spent and frequency could avoid the usability challenges discussed in Section 4.2.1. Complicated tools with several features embedded, such as cabling and moving, require more attention and effort from the user to fully comprehend and master.

Furthermore, Project Manager 1 remarked on the need to let future participants learn the 2D drawing of the machine room layout, especially those not under their responsibility. This notion is crucial as it helps facilitate a fruitful discussion.

A robust implementation

For a wide-scale adoption, VR-compatible hardware should be available at branch level across frontlines with sufficient support. This approach helps answer the concern of VR accessibility from Installation Supervisor 2. The project team hence can utilise it whenever and as often as needed. Furthermore, Project Manager 4 preferred the portable hardware set, allowing better flexibility to use in different locations when required. Wireless VR headset is also suggested because the users have more freedom to move around the play area without restriction as observed in the second and third testing sessions.

The VR software should run as smooth as possible to obtain the best user experience. All participants in the first user testing emphasised that synchronisation is required to work properly as it is the core mechanism for collaborative VR. Additionally, Project Manager 1 indicated the need for more development to make the current VR environment more intuitive and remove unnecessary complications in such tools. The suggestion enhances the user experience with natural object manipulation and reduces the time needed for training.

Most importantly, a comprehensive workflow structure is needed to facilitate the application of VR. The process of importing the BIM model in the VR process should be automatic to achieve minimum manual transferring. CSE 3 emphasised that VR software should extract 3D models from Revit and Navisworks, used for internal BIM implementation and clash coordination with clients, respectively. Such automatic processes must preserve BIM scale and texture while allowing users to manipulate the base model freely. CSE 3 noted that the complicated workflow to transfer BIM to VR used in this study should be avoided. Furthermore, the exporting process from VR needs more development to capture all information generated in the session. A reliable note-taking approach was then recommended by CSE 3. Project Manager 2, Installation Supervisor 2, and Project Manager 1 emphasised on the need to implement a robust transfer process of obtained information in VR to the installation team. Project Manager 1 noted that the field team often utilises paper drawing. An exporting option to such means of communication should be considered while conducting the development of VR.

Assessment and development suggestion on the features included in the VR environment

Table 7 indicates the importance ranking of features of the VR environment implemented in this study. Each feature is evaluated following a 5-point Likert scale (1 – Not a priority, 2 – Low priority, 3 – Medium priority, 4 – High priority, and 5 – Essential). The importance of all features except "Show tools instead of controllers" and "Move objects freely without restriction" is well-perceived since their modes are above 4. "Show tools instead of controllers" has the highest standard deviation, implying a significant division in opinions between respondents. This feature is regarded as not urgent with both mean and mode of 3. Interestingly, "Teleporting" and "Highlighting selected object" share similar results on having equal numbers of responses for each mode detected. Nonetheless, they are still considered a high priority with mean and median of 4.

Table 6. The importance of features implemented in the VR environment (sorted by mean)

Features	Mean	Mode	Median	Standard deviation	Wolfartsberger et al. (2017)
Measurement tool	4.8	5	5	0.44	C
Cabling tool	4.7	5	5	0.5	-
Ability to take a picture or video in VR	4.4	5	5	0.73	-
Teleporting	4	5*	4	0.87	B
Highlighting selected object	4	5*	4	0.87	A
Move objects freely without restriction	3.9	3	4	0.93	-
Show tools instead of controllers	3	3	3	1.22	C

* Three modes detected which are 5, 4, and 3.

Measurement tool is deemed as most essential (highest mean with mode of 5) by all participants (lowest standard deviation). Currently, the tool only utilises the International System of Units standard measurement, i.e. the metric system. As it would also be used in the US, it is crucial to implement the standard measurement system (e.g. feet and inches). It helps to avoid miscalculation caused by manual conversion between the two measurement systems. Besides, an auto-alignment option that helps users make accurate measurement lines between objects located far away was suggested. During the user testing, participants performed great distance measuring between i.e. motor and ceilings, room dimension, etc. most of the time. The current VR environment allows users to freely create a measurement line, which might result in the non-perpendicular line (line (1) in Figure 21) both horizontally and vertically. This suggestion is also applicable for small distance between objects as the same situation with the non-perpendicular measuring line occurs (line (3) in Figure 21). As the design review process depends heavily on the accuracy of the measurement tool, this suggestion is critical and requires attention.

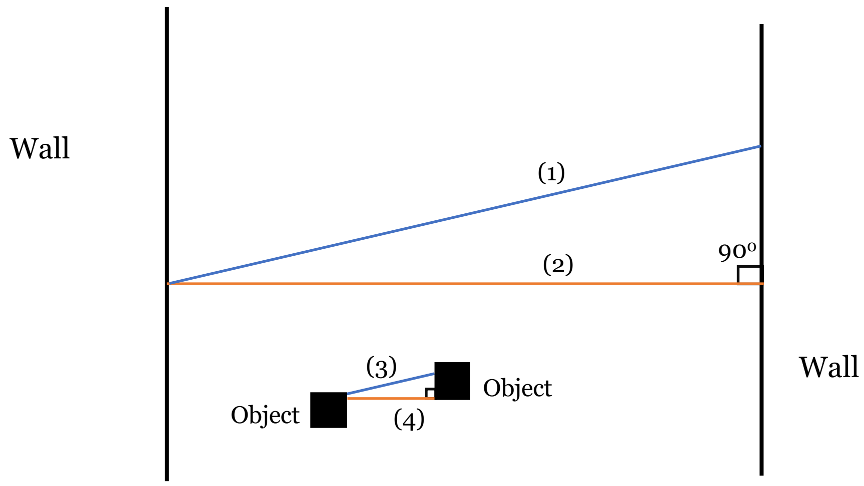

Figure 21. Measurement lines: (1) incorrect measurement line of great distance; (2) correct measurement line of great distance; (3) incorrect measurement line of small distance; (4) correct measurement line of small distance

All respondents also considered the Cabling tool as second most essential, implied from its second lowest standard deviation and highest mean. Participants in the first user testing suggested implementing a 10mm cable size to depict the low voltage cables in reality. It is important to note that the suggestion was then implemented in the second and third sessions. Moreover, Installation Supervisor 2 emphasised on making the "snap-to-surface" feature of the tool more automatic. The tool should allow users to draw cable vertically or horizontally in the air from any surface without the need to switch on and off the feature manually.

"Ability to take a picture or video in VR" follows in the ranking with the third highest mean. It is important to note that recording video is not supported natively in the VR environment. The Camera tool only enables capturing pictures of the VR scene. One of the CSEs emphasised the desire to export VR recording for showing to customers. The engineer remarked that showing videos is more practical than involving the client to use VR in case of early VR adoption. The clients might not have implemented VR yet; hence, VR is not applicable in the current market.

Evaluation and implementation suggestions on potential features in the future

Table 8 indicates the importance of potential features for future implementation. Each feature is evaluated following a 5-point Likert scale (1 – Not a priority, 2 – Low priority, 3 – Medium priority, 4 – High priority, and 5 – Essential). All respondents agreed on the urgency to implement the first three features in Table 8 as implied from the lowest standard deviations with the highest means and modes. Participants suggested developing "Reset object's position to its original place" further to the Undo feature. They emphasised the convenience of the ability to revert to a certain point of action. Besides, Project Manager 1 argued the Cabling tool should be complemented with a "Trunking tool" as trunking design is also challenging. The tool will help the team accurately identify future interference with all equipment, building structure and the MEP system.

Table 7. Potential features to be implemented in the future (sorted by mean)

Features	Mean	Mode	Median	Standard deviation	Wolfarts-berger et al. (2017)
Reset object's position to its original place	4.8	5	5	0.44	-
Trunking tool	4.7	5	5	0.5	-
Show object information (e.g. name of cabinets, dimension, etc.)	4.6	5	5	0.53	-
Select parts of the base model to interact	4.4	5	5	0.73	A
Export into BIM file	4.3	4	4	0.71	-
Move objects with realistic constraints	4.2	5	4	0.83	A
Note-taking tool	4.2	5	4	0.83	-
Importing documents (pdf, image, etc.)	4.1	5	4	1.05	-
Delete object	4	4	4	0.87	-
Disassemble object (e.g. motor) into smaller parts to interact	3.4	4	4	1.01	A
Haptic feedback (e.g. controllers vibrate when hit the wall, etc.)	3	4	4	1.58	-
Tagging people	3	3	3	1.22	-

Respondents also considered the following tools as high priority for future implementation with little variation in opinions: “Select parts of the base model to interact”, “Note-taking tool”, “Move objects with realistic constraints”, “Export into BIM file” and “Delete objects”. They all have high mean, mode and median scores above 4. Regarding the creation of realistic constraints, one of the CSEs gave examples on the outward door opening, sliding door, and equipment grouping (discussed in Section 4.2.1). Regarding the note-taking tool, one of the CSEs suggested the ability to add text, and this feature could be done via either a virtual keyboard or voice recognition.

Opinions between respondents are most divided on “Haptic feedback”, “Tagging people”, “Disassemble object into smaller parts to interact” and “Importing documents” with their standard deviations above 1. The first three features are deemed not urgent to implement as implied from their low means and modes. Though importing documents receives high rating, the significant variation between respondents’ perspective leads to the uncertainty in deeming it as high priority. This feature nevertheless might resolve the referencing challenge discussed in Section 4.2.1. Project Manager 1 and CSE 2 remarked on the idea of importing machine room layout in 2D drawing format into VR.

Some features to improve the practicality of VR in machine room planning that were not on the given list were also suggested. Participants from the first testing indicated the need for position locking. One of the CSEs elaborated that the base model should be locked by default. Users must unlock before making any adjustment, hence reducing unintentional movements of the object. A BIM data retrieving system was also recommended to facilitate “Show the object information” feature. The system should be accompanied by a component library which allows users to add any components when needed. CSE 2 imagined it as close to the digital twin concept.

Other features to enhance the general VR usability were also recommended. Auto-importing to VR from Revit and Navisworks, as discussed in the requirement (chapter 5.2.1.3), was mentioned. Moreover, Project Manager 1 suggested implementing brightness adjustment in the headset. Both the manager and CSE 4 argued that it might help increase the eye comfort for the user. However, adjusting brightness often depends on the hardware capability and needs more investigation in its implementation.

4.2.4 VR utilisation in practice

According to Figure 22, VR could be applied during all the stages of the process from planning to handover of the completed machine room. Figure 23 also shows that participants agree to use VR both internally and externally. However, it has been found that the adoption of VR heavily depends on different use cases and the nature of each project.

Stage to be implemented

The number of “agree” to “strongly agree” responses for each stage are the highest. Machine room planning in the frontline, design review and installation are significantly recommended with only “agree” and “strongly agree” responses. Some participants cast doubt or even disagreed with the use of VR in other stages.

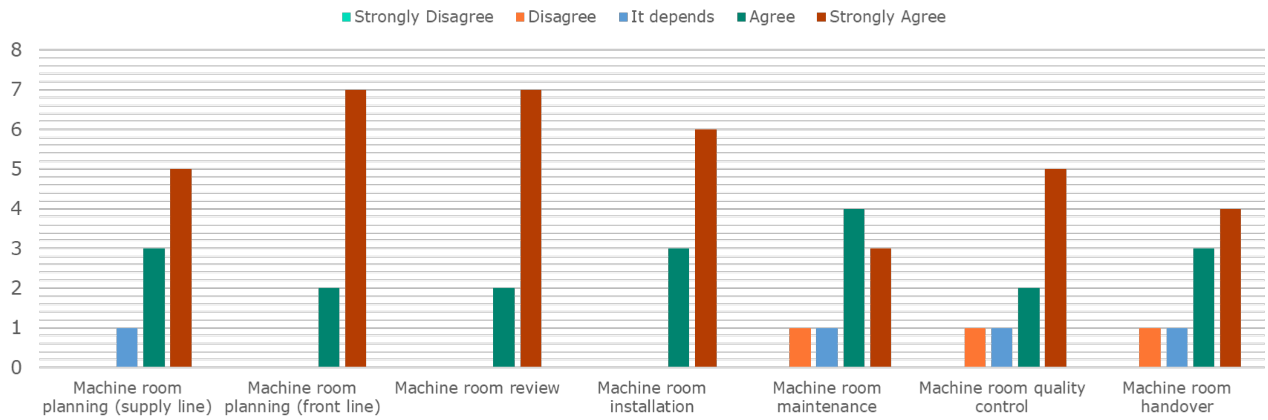

Figure 22. Participants' opinions on when to use VR in the current process of machine room planning, installation and maintenance.

It is suggested to use VR in major supply line engineering departments in Finland, China, and the USA. Project Manager 1 and CSE 2 indicated that supply teams could utilise VR for accurate material ordering. CSE 3 indicated VR could help ease the communication between the supply and front lines. Regarding the use of VR in the maintenance stage, some cast doubt and questioned the added value for the team. It is argued that maintenance teams often work in finished areas, in which the benefits VR brings might not justify its complicated implementation. However, VR can help the team check the maintainability of the equipment during the design process. Besides, VR was also recommended in the selling phase to demonstrate the aesthetic and the company's capability for the customers.

Most importantly, the use of VR should be determined on a case-by-case basis as emphasised by CSE 3 and in the survey. On a micro level, it depends on various project-related factors. First of all, not all projects have BIM implementation ready for VR. Secondly, constraints on resources such as budget for implementing BIM and VR training for the project team is another issue. Hence, the decision to use VR relies on the management board of the project. Finally, the engineering complexity of the project defines whether VR is needed or not. Participants foresee the added value of VR in high-rise projects that require tailored solutions and involve more safety risk. In contrast, volume projects which include standard design machines do not need to apply VR. On a macro level, market compatibility with VR implementation is another concern. Customers in some markets only expect 2D drawing, not even BIM. The market hence is not ready to fulfil the requirements discussed in Section 4.2.3. Applying VR then does not bring any benefits but rather serves as a marketing strategy for the company.

Proposed use cases

It seems collaboration within the team (option 1) and between teams (option 3) are in the highest interest with 8 "strongly agree" responses out of 9. Though having less "strongly agree" response (6 responses), individual work still gains positive feedback. External use with customers shares a similar positive reaction from the participants with one disagreed.

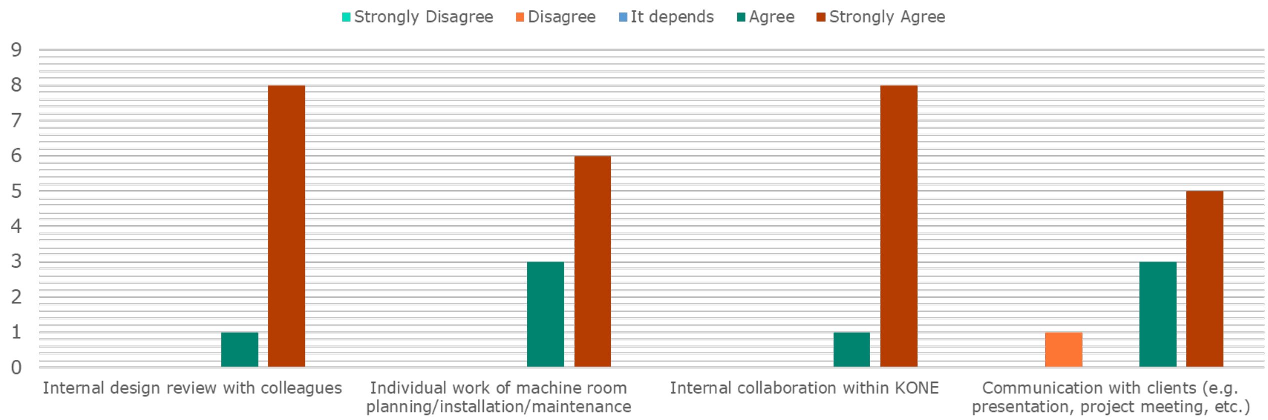

Figure 23. Participants' feedback on internal (the first three options) and external (the last option) use cases of VR.

The use of VR for individual work varies between roles. Though agreed that VR is beneficial, Project Manager 1 still cast doubt on the added value it brings for the manager's role because "I'm using a lot of Excel right now". Nonetheless, all participants found VR brings most benefits to the installation team in terms of visualisation for fitters and site logistic planning. Regarding collaboration between teams, CSE 3 emphasised on using VR for coordination meetings between supply-line and frontline. Installation Supervisor 2 indicated that the front-line team could also utilise VR to communicate design details with the installation team. Besides, Project Manager 1 disagreed with the external use of VR with the current development. The manager noted that clients might be demanding on VR implementation, which later causes more challenges for the construction company during the early adoption.

CSE 2 and Installation Supervisor 2 suggested the elevator pit and landing door could be the next target to apply VR in addition to the machine room. In such small areas, many equipment with complex fixing arrangements is located. Using VR to foresee potential interferences and plan the installation process can help minimise safety risks. Besides, the installation team's training can utilise VR due to the high immersion level and 1:1 scale of VR. Installation Supervisor 1 indicated new or less-experienced fitter will benefit most from such use cases.

5 Discussion

It is important to note that this study allowed users to conduct real tasks that participants often do in the current machine room planning workflow. Each participant performed testing on the actual project on which they were currently working. Therefore, it can be deduced that the results obtained are highly relevant and applicable in the context of the AEC industry. This chapter will discuss the critical findings in this study by combining the results from the interview before and during user testing as well as the literature review. The discussion is divided into several sub-chapters that correspond to the research questions. In the end, Section 5.7 summaries and answers them.

5.1 The inter-connected and networked nature of the current challenges in machine room planning

The challenges found from the interview are inter-connected. The underlying problems that are intertwined with others are complex communication, information-lacking 2D drawing, and non-standardised workflow structure. The impact of these problems is only recognized in the installation and later maintenance phases. For instance, inefficient communication with external stakeholders, found also in Zhang et al. (2020), together with the evolving amount of information leads to the lack of information for upfront planning in the construction phase. As a result, the planning cannot be conducted early enough, causing insufficient time for planning trunking and wiring. Strong division of teams leads to limiting the communication and collaboration between them, for examples between supply-line, front-line, quality controls, and maintenance. Inadequate means of communication and ineffective communication between supply-line and front-line cause design errors to be overlooked. Many studies (Gu et al., 2014; Wen & Gheisari, 2020; Wolfartsberger et al., 2018; Zaker & Coloma, 2018; Zhang et al., 2020) have raised similar issues. The issue of BIM availability was also discussed in Otto et al. (2005).

These problems directly affect the work of design and installation of the machine room. All monetary and time estimates that participants were able to provide in response to address the consequences (Section 4.1.1) originate from real-life examples of these problems. Hence, it can be implied that these problems are the most critical and need to be addressed immediately. Following improvement suggestions can be deduced: better flow of information, more effective means of communication and involvement between teams, and improved workflow structure with more planning. These inferences entirely fit with all improvement suggestions from the interviewees as indicated in Section 4.1.2.

5.2 Multi-user VR offers positive experience for the users

All interviewees and user-testing participants have limited to none experience with VR. Despite that, their response toward the application of VR remains positive before and after testing, even with those who did not participate in the experiment. High perception of spatial comprehension, real-scale and realism, which are highly anticipated and accounts for positive response from the interviewees before testing, was all confirmed during the experiment.

Participants in the user testing were considerably immersed in the virtual machine room. Some interesting signs of this immersion were that some sat on the floor to check beneath the machine, one of the supervisors tried to poke the other users for blocking his way, and some reported feeling of being on the actual installation site. A recent study (Zaker & Coloma, 2018) which conducted a similar experiment with a group of AEC professionals in a real-life project, reported similar positive responses from their participants. Participants expressed the feeling of being together in the same machine room with the ability to use both verbal and non-verbal communication despite being in different geo-locations, which was also reported in (Anderson et al., 2017).

Some challenges occurred during the user testing. Regarding the issue with usability of the collaboration environment VR environment in all testing sessions, the root cause was perhaps from the lack of time spent on learning to use VR. A minimum of 30 min for learning to use VR and the VR environment is found not to be sufficient for first-time or inexperienced users to smoothly perform complicated tasks such as drawing cables in machine room design review. The learning time in this study is much more compared to five-minute-learning reported in Zaker & Coloma (2018). The difference in the number of tools in the two VR environments might account for the situation. Moreover, motion sickness was reported only with the use of Oculus Rift S with higher frequency by the female user and shorter recovery time by the male user. This finding conforms with the result of Stanney et al. (2020) which indicated female users using Oculus Rift S had higher chance to experience motion sickness due to wider range of IPD non-fit compared to male users. Furthermore, an investigation on the synchronization issue in the first user testing suggests that unstable internet connection on that day might have been a contributing factor.

Major issues encountered in the sessions are deemed to have a negative impact on the user experience. Nonetheless, the overall experience was significantly positive and outweigh the challenges. All participants were captivated and even spent more time exploring the tool. Participants also asked to take some time in the testing session to perform actual collaborative design modification with their managers and remarked on the efficiency of collaboration via multi-user VR. Therefore, these findings suggest that project team members of the pilot projects involved in both interview and user testing are willing to adopt multi-user VR in the current machine room planning process for design review and as a means of collaboration. This conclusion helps resolve the concern brought up in the interview before testing that some people in the project team might not be willing to adopt the technology.

5.3 Both users and businesses can benefit from multi-user VR

Since the multi-user VR environment in this study utilises a BIM model to build the virtual environment, it can be deduced that this VR environment inherits all advantages that BIM offers. All benefits identified in this study experiment as discussed in Section 4.2.2 correspond to findings of many studies that investigate the use of immersive single-user VR (Flor et al., 2021; Gu et al., 2014; Zou et al., 2017) and multi-user VR (Abbas et al., 2019; Du, Shi, et al., 2018; Havard et al., 2019; Shi et al., 2016; Zaker & Coloma, 2018) in the AEC industry. These findings recognise a strong sense of presence in the immersive environment, the flexibility in viewing and an ease of communication as the foundation that generates other benefits according to the use case. Also, the concern of whether the benefits of BIM coordination in VR is significant compared to doing so via 2D screen, which was brought up by one participant in the interview before testing, was resolved by the time the testing completed. The participant, who later joined the user testing, recognized the effectiveness and efficiency that multi-user VR will bring in BIM coordination, thanks to the three fundamental advantages mentioned above.

Interestingly, improved confidence in design review has critical merit from the user perspective that has not been discussed in any studies to the best of the author's knowledge. This benefit not only brings considerable working satisfaction for the end-users but also helps project members gain more control in the construction phase. Project team members can utilise VR as a measurement proof, proving that the design layout complies with the set codes and standards as well as has enough room for cable and trunking routing. By doing so, participants in this study emphasised the control gained in planning site logistics over the installation subcontractor. Moreover, having machine rooms visualised in VR can also address the wish of one participant who hoped to construct the first machine room in a project as a template, with which to review and develop the others, saving time overall and reducing the risk of rushing.

From a business perspective, the findings reported in Section 4.2.2 also suggest the adoption of multi-user VR brings economic benefits to the current machine room planning process. Of all the stages, VR is found to be most economically beneficial in machine room design and installation, which was also concluded by (Guo et al., 2010). This finding corresponds to the economic value gained through studies (Guo et al., 2010; Haggard, 2017; Ozcan-Deniz, 2019) with real companies in the industry like. It is worth noting that time saving will ultimately become cost-saving. Economic benefits are mostly generated indirectly through improved design and better planning in terms of site logistics and coordination in installation. Cost saving can also be achieved directly through the reduction of time needed for BIM coordination meetings and seeking machine room design approval from the client, which is similarly reported in Syamimi et al. (2020). Besides, the enhanced branding image of the company as an economic benefit was also found in a similar case of BNBuilders (an American construction engineering firm) (Haggard, 2017). BNBuilders attracted more clients and won more contracts as the adoption of VR fit their image as an innovation-driven company. It can then be inferred that such monetary gain can also be applied to the other construction firms. Moreover, early design completion also allows the materials to be quantified more accurately and longer time for optimal sourcing to reduce cost and material waste. As multi-user VR enables remote collaboration with an immersive experience, the reduction in work-related travelling can help to save cost and time for companies as well as travel risk in the COVID-19 era (Bryant, 2006; Nayak & Taylor, 2009; Pratama & Dossick, 2019; Syamimi et al., 2020). Furthermore, decreasing the construction waste and travel can lower the carbon footprint in the AEC industry, hence contributing to the sustainability development through sustainable collaboration.

Performing a comparison on the benefits of applying the multi-user VR with consequential cost reported throughout Chapter 4 yields insights on potential cost saving. The results obtained from the user testing prove that multi-user VR could make the communication of design within the company and with external stakeholders as well as conduct site logistics planning more accurately and efficiently. Several tens of thousands of euros of extra materials and labour work to fix all conduits in an unexpectedly packed machine room as an afterthought caused by the use of information-lacking-2D-drawing and insufficient planning might have been saved. Similar amount of cost saving is also possible to address the problem of installing a missing component caused by insufficient communication between supply-line, CSE and the field team. Besides, 8-9 weeks of extra time due to miscalculated size of equipment and ineffective site logistics planning can be avoided. Involving clients to review the machine room design in multi-user VR can speed up the design approval process from couples of months to couples of hours. Using the VR environment for BIM coordination meeting between supply-line and front-line may shorten the meeting time to 30 minutes instead of 2-3 longer sessions.

5.4 Use cases and deciding criteria to apply multi-user VR

Statistically, the survey results illustrated in Figure 22 (Section 4.2.4) indicate that VR can be applied in all stages from tendering to handover of the machine room. However, machine room planning in the frontline, review and installation are the three stages that were emphasised through all comments in the survey and interview results after user testing. There were concerns regarding the cost-benefit ratio to apply this in the supply-line and quality control. This was raised in the interview before testing and remains valid after the testing. Many studies (Balzerkiewitz & Stechert, 2020; Noghabaei et al., 2020; Ozcan-Deniz, 2019; Whyte & Nikolić, 2018; Zhang et al., 2020) also indicated similarly that the majority usage of VR remains in design planning and review as well as construction planning. The beneficial findings in this study and (Guo et al., 2010) also address that those three stages benefit most from VR.

Regarding the specific use case, the survey results in Figure 23 (Section 4.2.4) illustrate that both internal and external usage of VR are well-received. The emphasis on using VR for internal design review, internal collaboration such as BIM coordination meetings between supply and frontline, and installation planning and training is significant both before and after user testing. Doubt on the benefit of using VR to communicate with clients remains valid before and after user testing. The concern of technological compatibility of the market, such as unavailability of BIM, lack of VR facilities, etc. reported by participants in the user testing of this study, Ozcan-Deniz (2019) and Otto et al. (2005) is the main reason. The high anticipation from the customer expectation found in the interview before testing may also contribute to the doubt.

Therefore, the use of multi-user VR is recommended in machine room planning by the frontline, design review, and installation as well as remains internal regarding the early adoption. There is a need to investigate the cost-benefit ratio of applying VR in the other stages since this study experiment addresses only design review and installation planning. In practice, multi-user VR can be used for (1) BIM coordination meetings between supply-line and frontline, (2) design review meeting between frontline team with field and maintenance team, (3) collaborative site logistic planning session for installation team and (4) communicating design and installation process to the installation team. This way of applying VR ensures a balance in cost and benefit, sufficient support from the company, and the help of BIM implementation whenever needed. It can be inferred that the stakeholders who are involved in design review and construction planning will benefit most from the proposed usage. In the context of KONE, those stakeholders are CSEs, Project Managers, Installation Supervisors, and Installers.

Most importantly, the application of VR must be considered on a case-by-case basis. Three deciding factors are proposed: readiness of market, team competency, and engineering complexity level. In some markets, BIM implementation is limited (Otto et al., 2005; Ozcan-Deniz, 2019). As models from clients are required to achieve a high level of accuracy in design review, this critical issue will hinder the coordination of BIM and ultimately the use of VR. At the moment, findings from this study and Whyte (2003) suggest applying VR only on projects that have significant engineering complexity such as large and major projects with multi elevator machine rooms. However, this recommendation remains vague. To address the issue, companies must set a limit of engineering complexity that determines which projects to apply VR so that the implementation cost of BIM and VR are justified by its benefits. For multinational corporations in the AEC industry like KONE, the limit should be set differently for each frontline because it essentially depends on the project team competency to implement BIM and VR.

5.5 The prerequisites for a successful adoption of multi-user VR in AEC companies

The yielded requirements from the participants in this study correspond to those in the literature. The main requirements still concern the accuracy of 3D model, onboarding and implementation robustness, and necessary features for VR software as discussed in section 4.2.3. In addition, other notable requirements regarding management perception towards VR and the need for a universal technical standard are also found for a successful adoption of VR in the AEC industry.

3D model and onboarding requirements

The requirements for the adoption of VR found in the interview before testing are similar to those reported after the user testing. The need to acquire highly accurate and complete models both from the company and client is critical. The quality of the proposed applications of VR above depends significantly on the 3D model (Ozcan-Deniz, 2019). The BIM coordination between the company and client plays an important role in this issue and requires more attention. The findings also suggest the need for more research on effective onboarding materials to use for VR. This is to address the concern of time-consuming and steep learning curve in the interview before testing. Ozcan-Deniz (2019) addressed the gap in VR-related knowledge within the industry and the need to keep employees or at least VR specialists in the company updated with all recent technological advancement.

Practical implementation requirements

Regarding VR hardware requirements, findings in this study suggest that VR hardware should be available at branch level for use whenever needed, i.e. front line head office or wherever the CSE engineering for major project is located. Balzerkiewitz & Stechert (2020) also indicated the need to invest in powerful hardware to avoid lagging caused by frame rate below 60 fps, which contributes to higher chance of motion sickness. Findings in this study and Stanney et al. (2020) favour the use of HTC Vive over Oculus Rift S since it has lower IPD non-fit range for both male and female. However, it does not mean that the use of Oculus Rift S should be avoided. The headset should be utilised with an understanding of the limitations. Furthermore, findings in this study indicate the critical importance of synchronization. High latency in transmitting information in collaborative sessions via multi-user VR can have a negative impact on the quality and efficiency of the decision-making in the AEC industry (Du et al., 2018). Two critical factors influencing synchronisation are identified in this study: internet connection quality and server stability. Companies developing multi-user VR must secure significantly stable server, while those adopting must ensure good internet connectivity for constant data transmission.

Regarding VR software requirements, it needs to facilitate an efficient import and export workflow in applying VR, which was also concluded by Zaker & Coloma (2018) and Balzerkiewitz & Stechert (2020). During this study, the exporting 3D model from Revit by its default exporting function caused the loss of texture of the model and required extra processing time to retain the texture. This issue was also reported by two AEC firms in a study by Pratama & Dossick (2019). The VR environment used in this study also could not retrieve information from BIM tools (Revit), which may hinder the benefits gained from multi-user VR in a data-driven industry (Du et al., 2018). As creating BIM-retrieving capable VR might take time, the current priority is to develop an immediate and automatic extraction of 3D models from BIM authoring tools (i.e. Revit and Navisworks) that preserves scales and textures of the models. Study by Du et al. (2018), Noghabaei et al. (2020) and Pratama & Dossick (2019) yield a similar conclusion. Moreover, Balzerkiewitz & Stechert (2020) also emphasized that VR software should be capable of exporting 3D models which can be used directly in different CAD and BIM software without further transformations. No standard file conversion between VR and BIM/CAD software is currently established; hence, manual format transfer is still required in the process of using VR. This finding addresses a similar concern posed by participants in the user testing.

Features required for machine room design review and planning

Two studies on using VR for product development process by Gabriel (2020) and Wolfartsberger et al. (2018) are referenced for comparison in this section. Gabriel (2020) tested the same VR environment based on DesignSpace VR software from 3DTalo. However, the VR environment tested in Gabriel (2020) does not include the cabling tool developed in this study. Besides, the ranking (descending scale of A, B, C in priority) of features of VR for design review found in Wolfartsberger et al. (2017) were included in Table 7 and Table 8 for comparison. It is worth noting that Wolfartsberger did not explain how the scale was established but mentioned that only features with A and B ranking were implemented. Hence, it can be inferred that ranking of such features corresponds to high priority, and essential in the study.

Regarding features implemented in the VR environment, “show tools instead of controllers” was deemed non-urgent, which corresponds with the results in both Wolfartsberger et al.

(2017) and Gabriel (2020). High priority ranking features such as teleporting and highlighting selected objects are also reported in Gabriel (2020) and corresponds to the A and B ranking in Wolfartsberger et al. (2017). However, the measurement tool, which is the most rated feature by everybody in this study, was deemed as low priority in both studies and even not implemented in Wolfartsberger's study. The difference in study objectives might account for the issue. Wolfartsberger et al. (2017) and Gabriel (2020) focused more on reviewing details components design of individual machines that involved many steps of disassembling and reassembling while this study aims for reviewing the overall layout of the machine room for planning. The measurement tool in machine room design plays a pivotal role since the process requires checking distances of many components against each other as stated in the regulation. However, a similar case study by Zaker & Coloma (2018) on construction layout design review find measurement tool essential for their experiment. Hence, findings in Table 7 suggest that all features implemented in the VR environment should be kept for the final production of the VR software, except "showing tools instead of controllers". Most importantly, more development to address the improvement suggestion in section 4.2.3 is highly recommended. One of the key improvement requests is adding the standard system and auto-alignment options into the measurement tool for more accurate measuring. The auto-alignment options should automatically create a perpendicular – 90 degree measuring line from one object surface to another's (line (2) and (4) in Figure 21). Enhancing the intuitiveness of the cabling tool is also essential. Implementing native video recording might be considered but not a priority.

Regarding features for future implementation, Wolfartsberger et al. (2017) and Gabriel (2020) yield a similar conclusion on the high priority of "moving objects with realistic constraint" and "select parts of the base model to interact". However, "disassemble object into smaller parts to interact" was found non-urgent with strong division in opinions in this study while both Gabriel (2020) and Wolfartsberger et al. (2017) reported it to be a high priority. It can be inferred that the study objective differences result in this issue. Machine room design review addresses the overall layout without the need to disassemble each equipment into smaller parts. In contrast, this feature is essential in Wolfartsberger et al. (2017) and Gabriel (2020) as they aimed to review the construct of individual components in an equipment. Overall, the findings in Table 8 suggest the immediate need to implement the following features in a descending order of priority: Reset objects to its original position, Trunking tool, Show object information, Select parts of the base model to interact, and Export to BIM file. Gabriel (2020) also emphasised on the importance of the ability to reset object's position. "Show object information" was envisioned by participants to directly retrieve from BIM authoring tools (i.e. Revit), which will take significant time to investigate and implement. Hence, minimum requirement for the information shown includes object name and dimension. Such BIM-retrieving VR systems developed by Anumba et al. (2010), Du et al. (2017) and Du et al. (2018) are suggested for the initial investigation. "Note-taking" and "Move objects with realistic constraints" should also be considered if there is extra resource. Other features not included in Table 8, such as position locking and brightness adjustment, though reported beneficial by participants, need further usability study to understand how it should be done. This study does not have sufficient evidence and insights to address those features.

Other requirements

Many studies (Noghabaei et al., 2020; Zaker & Coloma, 2018) have found resistance to adopt technology by the lack of upper management knowledge is the major factor in the low adoption rate of VR in the AEC. Specifically, Zaker & Coloma (2018) found that increased user awareness of VR can lead to more consideration. However, this study found that interviewees before testing have a high awareness level of VR since their assumption without even using VR matched with the findings yielded after the user testing. Only when they have the chance to try it out in a real project, the consideration towards VR ignites. Hence, increasing awareness through conventional medium such as video, presentation, report, etc. might not have enough persuasiveness. It is suggested that potential users and decision-makers should be given a chance to try out the use of multi-user VR in the current process.

The willingness to adopt VR is only significant when companies understand the true costs and benefits (Noghabaei et al., 2020). Therefore, there is an emerging need for empirical research on true implementation cost and savings (i.e. cost- and time-wise) of VR in both academia and industry. Nonetheless, it is important to note that achieving such research outcomes is challenging. Implementation expenses in a company does not only involve hardware cost but also others like supporting personnel, training, subscription fees, etc. True cost saving might also be challenging to obtain especially in the case of elevator machine rooms. Extra costs in response to defects occurring in the machine room cannot be recognized and quantified immediately. These challenges should also be addressed in future research.

The ineffectiveness in conducting information transfer between BIM and VR encountered in this study and Pratama & Dossick (2019) perhaps results from the lack of a technical standard regarding VR. The challenges were also raised by many studies (Du et al., 2018; Noghabaei et al., 2020; Ozcan-Deniz, 2019). Therefore, such standards and guidelines in defining technical requirements for data transferring should be developed by the collaboration between the academic community and the AEC industry. A brief review on the current development of such standards by Brennesholtz (2018) may provide an initial insight on developments in the future.

Overall, there are general needs and priorities for industrial use of VR regardless of application. The use of BIM to create accurate 3D model for VR environment is fundamental. Investment in powerful VR hardware that can handle complex VR scenes is necessary (Zaker & Coloma, 2018). This helps to avoid health-related issue that could negatively affect the user experience of VR. Besides, such VR hardware should be made as much available as possible to potential users. An automatic and fluid communication between BIM and VR software is needed to facilitate the early adoption in the current workflow. On the other hand, there are still application-dependant needs for different use cases as discussed earlier in this section. Hence, the applied VR software should have correct functionalities and features needed for each use case to enables full potentials of this technology.

5.6 Limitation of the study

One limitation of this study is the dissimilar VR hardware usage for different front line. For instances, the use of wired VR headset might restrict movement of some participants compared to those using wireless ones. The lack of facilitator in the first user testing also makes the facilitation challenging. Participants in the front line without facilitator could not receive enough instruction and help while using VR. This issue might have a negative impact on the overall user experience. Moreover, the differences in onboarding duration for each participant might also affect how users perceive the easiness of use of the VR environment. Those with shorter onboarding time tend to struggle more frequently than the ones with more learning time. In addition, all participants in this study are not familiar with using VR headset, controllers and functionalities of VR software. In the experiment, they have only one session to learn how to use VR and perform the given tasks. Evidence through studies (Hill & Howarth, 2000; Howarth & Hodder, 2008) have shown that more frequent use of VR enhances user experience to easily perform tasks and reduces motion sickness. Hence, future research could improve the overall user experience by increasing the number of repeated VR exposures.

Another limitation is the small number of participants in the user testing. Therefore, more advanced statistical analysis cannot be performed. However, it is important to note that this study's approach is qualitatively driven. Hence, the study provides direct and more relevant insights from the user perspective to the AEC VR research community and industry. Furthermore, the nature of entirely remote testing also hinders the author's observation ability when conducting the test.

5.7 Answers to the research questions

Question 1: What are the challenges of the current machine room planning, installation, and maintenance?

Figure 24 illustrates current major challenges in the elevator machine room planning. A detailed explanation can be found in Section 4.1.1 along with other notable challenges. Most importantly, they are inter-connected, which means the impact of one can lead to the cause of others. All estimates on the monetary and time value of the consequences found in this study originate from the following challenges: complex communication internally within company and with external stakeholders, the use of information lacking 2D drawing, and non-standardised workflow structure. These challenges result in the insufficient collaboration and ineffective communication between the supply-line and frontline teams. Their impacts are only realised in the installation and later in the maintenance phases, which is considerably costly to resolve. Therefore, these challenges deemed critical and require immediate response. This inference not only conforms to the improvement suggestions by the interviewees (Section 4.1.2) but is also concluded in many academic studies (N Gu et al., 2014; Wen & Gheisari, 2020; Wolfartsberger et al., 2018; Zaker & Coloma, 2018; Zhang et al., 2020).

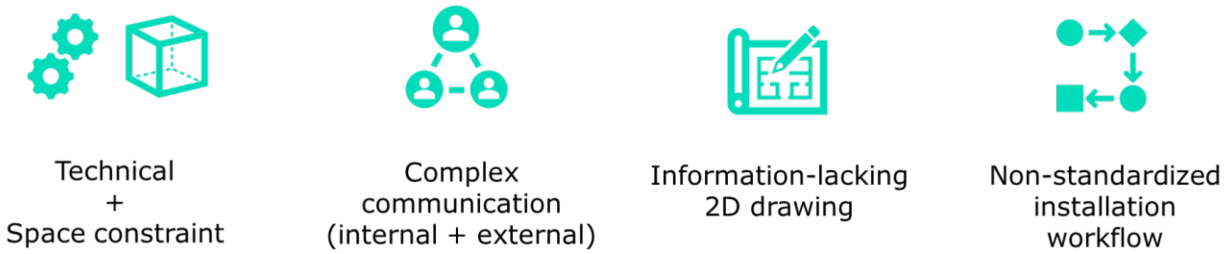

Figure 24. Key challenges in the current machine room planning, installation and maintenance.

Question 2: What are the benefits of applying multi-user VR from the user and business perspective in the current machine room planning, installation, and maintenance?

Figure 25 demonstrates the benefits from the user and business perspectives of multi-user VR found in this and other academic studies (Abbas et al., 2019; Du, Shi, et al., 2018; Havard et al., 2019; Shi et al., 2016; Zaker & Coloma, 2018) in the AEC industry. The multi-user VR environment in this study is BIM-based; hence, it inherits benefits also from the implementation of BIM. It is important to note that the benefits of multi-user VR are case-dependent and only present when applied appropriately. The technology itself is not the ultimate solution but rather its overall implementation within a company. For instance, implementing multi-user VR will require conducting BIM, hence improving the digitization of the design and construction process.

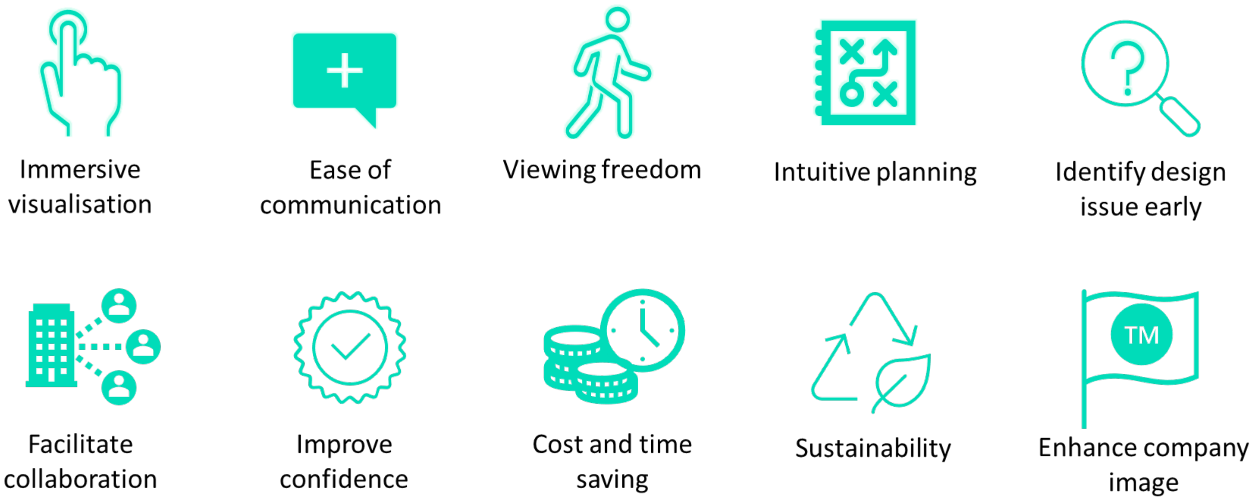

Figure 25. Benefits of multi-user VR in the AEC industry.

From the user perspective, multi-user VR provides a much more intuitive planning tool that enhances the project teams' collaboration, effectiveness, and efficiency as compared to the current use of 2D drawing, and even when the BIM authoring tool (i.e. Revit) is used. The ability to provide real-scale immersion, ease of communication via both verbal and non-verbal cues, and freedom of viewing the construction model account for these significant benefits. Participants in this study have stated that critical design issue, which are often overlooked, can be easily identified in VR. By using real-scale measurement as a proof, they gain more confidence in the machine room layout design and control in the installation phase. This merit has not been reported in any studies to the best of the author's knowledge. It is also important to note that participants in this study are captivated by their VR experience and even willing to stay longer to learn about its use. With the improved confidence in design review and excitement in the technology, their work satisfaction is elevated. Overall, multi-user VR could help to resolve the challenges with communication and the use of 2D drawing in the process.

From a business perspective, multi-user VR potentially helps to save several tens of thousands of euros by improving communication and planning. Time needed for remote collaboration between teams within the company and seeking clients' design approval can be shortened significantly. It is important to note that all time saving will later result in cost saving in reality. Early design planning allows more time for accurate material estimation and optimal purchasing that reduce cost and up to 30% of waste. These benefits are more pronounced in this Covid-19 era. With the reduction in waste and travelling, multi-user VR also helps to create a more sustainable collaboration within the industry. Moreover, the application of multi-user VR enhances the image of AEC firms that are innovation- and sustainability-driven. This benefit also brings business value to companies through better market competitiveness that might result in more contract awarded as found in Haggard (2017).

Question 3: How multi-user VR should be applied in the current machine room planning, installation, and maintenance?

Participants in this study state that multi-user VR can be applied both internally and externally as well as at all stage from tendering to handover and even in the sales phase (Figure 22 and 23 in Section 4.2.4). However, multi-user VR should be utilised internally in machine room planning by the front line, design review and installation stage in the early adoption. This approach balances the cost and benefit of the technology and ensures sufficient support for the use of VR and BIM implementation from the company. Recommended specific use cases are:

- BIM coordination meetings between supply-line and frontline
- Design review meeting between frontline team with field and maintenance team
- Collaborative site logistic planning session for installation team
- Communicating design and installation process to the installation team.

To this extent, these following stakeholders in the design review and construction planning should be involved: design engineer, project manager, installation supervisor, and installer. They also benefit directly from the use of multi-user VR. Moreover, multi-user VR must be applied with the consideration of a case-by-case basis as well as market readiness, team competency and the project's engineering complexity. Even though this study and Whyte (2003) propose multi-user VR to be used in complex projects, each company must set an engineering complexity limit to decide which projects to apply. The limit should be tailored to each front line in AEC multinational companies that suits each project team competency and market readiness.

To adequately apply multi-user VR, AEC firms must meet several requirements. As the quality of planning in VR heavily depends on the 3D model, BIM implementation with the inclusion of both company's and client's equipment is required to generate the accurate and complete 3D model. Most importantly, AEC companies must establish a process of effective knowledge transferring between designers, engineers and field employees. Field employees have the expertise and experience to define the essential needs in machine room design. It is important to direct such knowledge to designers and engineers for accurate BIM conducting. It is also pivotal for designers and engineers to communicate design details to field employees so that they can make informed decisions onsite. Moreover, VR hardware should be available at branch level so that concerned stakeholders can access whenever needed. VR computers must be powerful enough to sustain 90 fps with preferably wireless VR headsets and stable internet connection. Upper management should also be given a chance to experience the use of multi-user VR in the process and provided with a true cost-benefit analysis. In addition, quick and effective VR training materials should also be developed to facilitate the adoption of multi-user VR in the workflow.

The future adopted VR software should include all features implemented in this study's VR environment with some improvement as discussed in Section 4.2.3. A standard system and auto-alignment option should be included in the measurement tool. The intuitiveness of the cabling tool should also be enhanced. Moreover, new features as discussed in Section 5.5 should be introduced: Reset objects to its original position, Trunking tool, Show object information, Select parts of the base model to interact, and Export to BIM file. Besides, the implementation of automatic transfer from BIM to VR that preserve scale, texture and information is required to establish a smooth workflow. Direct transfer from common BIM authoring tools such as Revit and Navisworks are prioritised.

6 Conclusion

This study has investigated the use of multi-user VR proof-of-concept for collaborative elevator machine room planning via case study. The design thinking model by Stanford Design School is utilised as a methodological framework. The VR collaboration environment has been built based on DesignSpace – a VR-based design software by 3DTalo. Four real-life major elevator projects from KONE in the USA, Malaysia, Indonesia, and the UAE have been involved. The study starts with interviewing the project teams to identify the current challenges in the process and what they as the users expect from VR. The VR environment is then developed based on the insights generated from the interview and related literature. Three cross-country user testing sessions are conducted to test out the VR environment. After each session, a group interview is carried out to collect feedback from the participants. A questionnaire is also distributed to each participant to systematically collect their responses on how multi-user VR could be used and improvement suggestions for the VR environment.

Insights generated in this study present a view from the AEC industry. Participants are real-life project team of the involved projects. They also performed real-life tasks as they often do on the actual BIM model in their current workflow. Many benefits of multi-user VR from both user and business perspective have been identified. An estimate of potential cost and time saving is also established to contribute to the AEC academic community. Practical implementation requirements for multi-user VR are provided for future adoption of the technology in the industry. Emerging features needed for a better user experience in VR are also suggested.

As there is still a gap in the knowledge of VR between researchers and practitioners (Ozcan-Deniz, 2019), future research should focus on merging the knowledge of both. More empirical studies on the true cost of implementation and savings in terms of cost and time should be conducted. Financial investment on VR in the industry can then be considered by the upper management as they can understand the cost-benefit analysis of the technology. To facilitate the adoption of VR in the current workflow of the AEC industry, future studies should focus on improving the fluid communication between BIM authoring tools and VR. This will later become an emerging need as VR users in the AEC industry have to work with both technologies at the same time. More research into developing the usability of VR that requires less time for training to reduce implementation cost is also recommended.

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Appendix

VR User Testing Questionnaire

INTRODUCTION: This survey is to collect your feedback after the VR user testing session. It will take 10 - 15 min to complete the survey. No personal information is collected for the survey. Please contact Phong at phong.truong@kone.com if you have any concern regarding data collection and the survey.

QUESTION 1: Which front-line unit are you from?

- Indonesia
- Malaysia
- Dubai
- USA
- Other: (written response)

QUESTION 2: Please rate the statements in question 2 based on the scale from Strongly Disagree, Disagree, It depends, Agree to Strongly Agree.

- I would like to recommend using VR in ...
    - Machine room planning (supply line)
    - Machine room planning (front line)
    - Machine room review
    - Machine room installation
    - Machine room maintenance
    - Machine room quality control
    - Machine room handover

- If you choose "It depends", please explain why you choose it for each applicable options:

- If there is any other phase in the process that you would like to recommend applying VR, please write it here:

QUESTION 3: Please rate the statements in question 3 based on the scale from Strongly Disagree, Disagree, It depends, Agree to Strongly Agree.

- I would like to recommend the following use case of VR in machine room planning/installation/maintenance:
    - Internal design review with colleagues
    - Individual work of machine room planning/installation/maintenance
    - Internal collaboration within KONE
    - Communication with clients (e.g. presentation, project meeting, etc.)

- If you choose "It depends", please explain why you choose it for each applicable option:

- Please also suggest other use cases if they are not listed above:

QUESTION 4: Please rate the priority to implement the following functionalities (1 – Not a priority, 2 – Low priority, 3 – Medium priority, 4 – High priority, and 5 – Essential):

  - Teleporting
  - Select parts of the base model to interact
  - Disassemble object (e.g motor) into smaller parts to interact
  - Highlighting selected object
  - Delete object
  - Move objects with realistic constraints
  - Move objects freely without restriction
  - Reset object's position to its original place
  - Measurement tool
  - Cabling tool
  - Trunking tool
  - Note taking tool
  - Tagging people
  - Importing documents (pdf, image, etc.)
  - Show tools instead of controllers
  - Ability to take a picture or video in VR
  - Haptic feedback (e.g controllers vibrate when hit the wall, etc.)
  - Show object information (e.g name of cabinets, dimension, etc.)
  - Export into BIM file

- Other functionalities you would like to add with priority rating (please write following the "Name of the function - Priority" rating format):

- Please write here if you have other comments:

QUESTION 5: If you have any other comments or suggestions, please write it here:

THANK YOU FOR YOUR PARTICIPATION!

Please contact me via Teams or phong.truong@kone.com in case of questions, comments, and suggestions.